1971

Effect of tile drainage on trafficability for agricultural equipment

Abdul Satar Younis Aldabagh
Iowa State University

Effect of tile drainage on trafficability for agricultural equipment

by

Abdul Satar Younis Aldabagh

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subjects: Agricultural Engineering
Civil Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Heads of Major Departments

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Ames, Iowa

1971

TABLE OF CONTENTS

INTRODUCTION

Definition and General Trafficability Considerations

Agricultural and civil engineers are becoming increasingly aware of the need for knowledge of soil-vehicle relations. The term soil trafficability was developed in connection with off-the-road vehicles. Trafficability may be defined as the capacity of a soil to withstand vehicular traffic. The trafficability of a soil is considered adequate for a given vehicle if the soil has sufficient bearing capacity to support the vehicle and sufficient traction capacity to enable the vehicle to develop the forward thrust necessary to overcome its rolling resistance. As soil conditions grow worse and bearing capacity and traction capacity decrease, rolling resistance increases. When the rolling resistance is equal to or greater than the forward thrust, the vehicle becomes immobilized.

Normally a vehicle is immobilized by a concurrent failure in bearing and traction, and it is difficult to separate the two effects. Traction failure can occur in a soil with adequate bearing strength, as when a rubber-tired vehicle merely spins its wheels but does not sink appreciably. Sinkage failure does not occur, however, without being accompanied by traction failure.

Terminology

Specialized terms used in connection with trafficability investigations are defined as follows:

bearing capacity -- The ability of a soil to support a vehicle without excessive sinkage of the vehicle.

cone index -- An index of the shearing resistance of soil obtained with the cone penetrometer. The value is a dimensionless number representing the resistance to penetration into the soil of a 30-degree cone with 1/2 square inch base area. The number, although considered dimensionless, is actually pounds of force on the handle divided by area of the cone base in square inches.

critical layer -- The soil layer in which the rating cone index is considered a most significant measure of trafficability. Its depth varies with the weight of vehicle and the soil profile, but it is normally the layer located six to twelve inches below the surface.

mobility -- The ability of a vehicle to move on a land surface.

mobility index -- A dimensionless number which results from a consideration of certain vehicle characteristics.

rating cone index -- The product of the measured cone index and the remolding index for the same layer of soil; it expresses the soil-strength rating of a point subjected to sustained traffic.

remolding -- The changing of the natural structure of a soil by traffic, or by a remolding test. Remolding may have a beneficial, neutral, or detrimental effect, resulting in a change of soil strength.

remolding index -- The ratio of remolded soil strength to original strength.

slipperiness -- The low traction capacity of a soil surface owing to its lubrication by water, mud, or snow.

stickiness -- The ability of a soil to adhere to vehicles.

traction capacity -- The ability of a soil to resist the vehicle-tread thrust required for steering and propulsion.

trafficability -- The capacity of a soil to withstand vehicular traffic.

vehicle cone index -- The index assigned to a given vehicle that indicates the minimum soil strength in terms of rating cone index required for 50 passes of the vehicle.

Development of Trafficability Analysis

Trafficability studies were first directed toward finding a simple instrument to measure the strength of the soil. Since soil in the field is inherently quite variable, the instrument had to be easy to use so that a large number of readings could be made within a short time. The variation of soil properties with depth is important, therefore it was essential that the instrument be capable of use at some depth below the surface. The instrument that evolved from these studies is the cone penetrometer (20).

In trafficability studies, bearing-traction capacity is measured empirically in terms of the cone index. It is the pounds of force that must be applied to the handle of the cone penetrometer per square inch of end area of cone tip in order to force it into the ground.

Many fine-grained soils whose strengths are low in situ will become even weaker under the action, or remolding effect, of a vehicle. The strength loss with traffic is measured with remolding test equipment. The remolding index of the soil is a ratio that expresses the fraction of the original, undisturbed soil strength that can be considered to be available to support traffic when many vehicle passes are to be made. The final measure of a soil's trafficability is the rating cone index, which is obtained by multiplying the in situ cone index by the remolding index.

From data collected in hundreds of tests with many vehicle types on several types of fine-grained soils in widely scattered locations, it has become feasible to predict the performance of vehicles on the basis of the rating cone index. If this index for a given area is known, one can predict confidently whether a given vehicle will be able to cross it once, whether 50 vehicles can cross in the same path, how heavy a load the vehicle can tow through it, or how steep a slope the vehicle can climb (31).

Objectives of Study

To be adequate for passage of a vehicle, a soil must have sufficient bearing capacity to prevent the vehicle from sinking too deeply and sufficient traction capacity to provide the necessary forward thrust of the vehicle's wheels or tracks. Weather conditions produce changes in the trafficability of agricultural soils. In rainy periods, fine-grained soils undergo an increase in moisture, with resultant increased slipperiness and stickiness and decreased strength. Dry periods have opposite effects. Since tile drainage systems are designed to remove excess moisture from poorly drained soils, the installation of tile drains will improve the trafficability of soil and, therefore, facilitate timely tillage operations. The specific objectives of this study are:

1. Develop relations between moisture content, depth to water table, and soil strength from field measurements in poorly drained soils
2. Conduct laboratory tests to develop relation between soil strength and moisture content and compare this relation with that obtained from field measurements
3. Relate soil strength to mobility of agricultural equipment and perform trafficability tests with an agricultural tractor
4. Use existing data to find the effect of tile drains on water table fluctuations and estimate the added

economic benefit of tile drainage from the trafficability standpoint.

REVIEW OF LITERATURE

Trafficability studies were initiated in 1945 by the governments of the United States, Great Britain, and Canada. Since then considerable interest has developed in methods and techniques for evaluating vehicle performance in soft soils for efficient use of ground machines in military and civilian off-road operations (5, 6, 7).

Many reviews and summaries have been written on soil trafficability. The United States Army Engineer Waterways Experiment Station, Corps of Engineers, has written a summary of the studies it conducted through calendar year 1955 (44). Another summary, written by the Waterways Experiment Station, included the studies made through calendar year 1963 (43). Knight and Rula (21) presented a summary description of instruments and techniques developed by the Corps of Engineers, United States Army, for directly measuring and remotely estimating the trafficability of fine-grained soils. The Department of the Army (49) has written a chapter which describes the standard cone penetrometer and the soil sampling and remolding equipment and explains their care and use. A similar chapter was written by the United States Army Engineer School (38).

History of Trafficability Study

The problem of trafficability was given special attention during World War II, when vehicle immobilization caused the United States ground forces to suffer reverses in various theaters of operation. Most of the work on the subject of soils trafficability prior to 1948 has been accomplished by the United States Corps of Engineers, the United States Ordnance Department, the United States Navy, the British Government, and the Canadian Government.

The United States Corps of Engineers became interested in the problem of soils trafficability in 1942, when tests were conducted in Arizona and California to improve the mobility of vehicles in desert terrain (45). Low-pressure tires were developed for trucks operating in sand, which proved to be a reasonable solution for many of the mobility problems in sand. At the end of 1943 the effectiveness of low-pressure tires was tested in mud. In 1944 a study was conducted on methods of passing equipment over terrain similar to rice paddy fields, and in 1945 an extensive study of the problem was accomplished (45).

The United States Ordnance Department has pioneered in developing a land locomotion mechanics that emphasized the physical relations between the structure of vehicles and the environment of their operation. Many of the studies were theoretical, but with the aid of scale models they were frequently extended into experimental studies for verification of principles. Full-size experimental vehicles were developed and evaluated by the Ordnance Department so that the overall soil-vehicle system can be studied (15). The Ordnance Department has also developed two field instruments for measuring soil characteristics under reconnaissance conditions. One of these is a probe which is forced into the ground at a constant rate, and the other, a flat plate to which shear vanes are attached (45).

The United States Navy's interest in trafficability is in connection with landings on beaches. In 1945, tests were conducted in which three factors were considered to control the trafficability of beaches. These are: the consistency or hardness of the beach material in place, the grain-size characteristics and moisture content of the beach material, and the gradient of the beach. Due to time limitations, an empirical approach to the problem was followed rather than a theoretical approach based on bearing pressures of the vehicles versus the bearing capacity of the soil.

The British have conducted trafficability studies in Great Britain and in other parts of the United Kingdom. In 1944 they established a Committee on Mud-Crossing Performance of Track-Laying Armoured Fighting Vehicles, and studies were conducted with regard to improving track vehicle design and predicting the trafficability of soil. Their work has followed a theoretical approach to the problem and the primary emphasis has been on vehicle design. Shortly after the end of World War II, the Fighting Vehicles Research and Development Establishment in England developed a hand-operated vane shear device as a primary soil-strength-measuring instrument in mobility research. This device, designed to provide a rapid determination of the *in-situ* shear strength of the soil to depths of several feet, has been used extensively by the British in both laboratory and field studies (42).

The Canadian work has followed, to a large extent, the British approach from the theoretical standpoint. Their work has been directed more toward improving vehicle design than toward predicting the trafficability of soils. In 1945 they established the Associate Committee on Soil and Snow Mechanics of the National Research Council. This Committee proposed a field soil testing device in which both normal and horizontal loads can be applied. It was expected that the cohesion and angle of internal friction could be determined with this instrument (45).

Factors Affecting Trafficability

There are several factors that influence the trafficability of soils. The principal factor affecting the trafficability of a soil is its shear strength. Physical soil properties that affect the shear strength of a soil include moisture content, grain size, grain shape, mineralogical composition, organic content, plasticity, and density. The existing soil strength of natural soils is also influenced by the specific conditions that prevailed during formation or deposition of the soil, and by subsequent cycles of wetting and drying.

Moisture content is the principal factor that affects the strength of a given soil. A fine-grained soil in a comparatively dry state may be trafficable to all vehicles, but at a higher moisture content, its strength, and consequently, trafficability, may be such that only certain vehicles can pass. At even higher moisture contents the soil may be untrafficable for all vehicles.

In 1948 the United States Army Engineer Waterways Experiment Station (46) conducted laboratory tests to obtain information on strength and stickiness characteristics of a wide range of soils at various moisture contents and densities. These tests were made on soils ranging from coarse to fine-grained. It was found that the strength, as measured by the cone index, was generally the highest at the lowest moisture content and decreased with an increase in moisture. Exceptions to this trend occurred in the coarse-grained soils and in a few of the fine-grained materials of low plasticity; in these instances, the strength reached a maximum at an optimum moisture content and decreased with both an increase and a decrease in moisture. The Waterways Experiment Station (42) conducted another laboratory study in 1964 to investigate strength-moisture-density relations of fine-grained soils. The study consisted of soil strength measurements on heavy and lean clay samples, molded in the laboratory at three different densities for each clay, and at six moisture contents ranging from the plastic limit to about midway in the plastic range.

Soil strength can be evaluated by direct measurements, but for areas where access is denied, it must be estimated remotely, utilizing knowledge of the area and relations developed from data on analogous environments. Since change in strength is principally dependent on change in moisture content, methods for predicting soil moisture content change were developed as a prerequisite to finding methods for forecasting trafficability of a soil (39, 40, 41). The soil moisture prediction methods which were developed first in the United States were found to be applicable to tropical soils in Panama, Colombia, Costa Rica, and Puerto Rico (28, 26, 27, 17). Kennedy et al. (16) investigated changes in moisture-strength conditions with passage of time as a basis for the development of moisture-strength prediction methods applicable to Southeast Asia. They reported that the patterns of daily moisture change in Thailand were similar to those found in the United States upon which soil moisture-prediction method was developed. They also stated that

> The water table influence is the greatest source of error in predictions using specifically derived relations. Modifications in the prediction method are needed to account for time of occurrence and duration of the water table effect. The capability of identifying soils and sites subject to water table influence is also needed.

Bassett and Meyer (2) conducted a study to determine and evaluate the soil, site, and weather factors that affect significantly the inception, duration, and periodicity of seasonal high water tables, and to explore means by which the moisture-prediction method could be modified to improve its accuracy when applied to soils with high water tables. They reported that inception of high water tables was significantly affected by cumulative precipitation and topographic position, while duration of high water tables was affected by topographic position, slope, depth to relatively impermeable layer, and precipitation. They found that periodicity of high water table was influenced by topographic position, amount of precipitation, rate of evapotranspiration, and where applicable, stream or river stage. They also stated that

> The accuracy of predicting moisture content by means of the moisture-prediction method at sites with high water tables was improved by assuming that moisture contents remain at field maximum when depths to water tables are predicted to be less than six inches. The accuracy of moisture content predictions was improved further by using special depletion rates during periods in the summer when depths to water tables were predicted to be less than three feet.

Vaigneur (50) and Vaigneur and Johnson (51) developed design criteria for the spacing of tile drains in agricultural soils by determining the proportion of precipitation that produced the need for drainage and by relating this accumulation of excess moisture to the behavior of the water table for various drain spacings and soil conductivities. A tile depth of four feet, a tile diameter of 0.5 feet, and a depth to the impervious layer below the drain of four feet were used.

Slipperiness and stickiness are two other soil properties that affect the movement of a vehicle. Slipperiness is a condition of deficient traction capacity in a thin surface layer of a soil which otherwise is trafficable. A vehicle immobilized solely because of slipperiness spins its wheels but neither moves forward nor sinks excessively. Stickiness is the ability of soils to adhere to vehicles. It will occur in all fine-grained soils when they are comparatively wet. The greater the plasticity of the soil, the more severe are the effects of stickiness. In general, stickiness will have adverse effects on the speed and facility of travel and steering of all vehicles, but will not in itself cause the immobilization of any vehicle except small vehicles.

Critical soil layer is another factor affecting soil trafficability. Correlation between vehicle performance and soil strength are more consistent when the strength in the critical layer is considered. The depth of the critical layer varies with the soil's strength profile and the vehicle type and weight. In fine-grained soils and sands with fines, the normal depths of the critical layer for wheeled and tracked vehicles are as follows (49):

Type of vehicle	Depth of normal critical layer, in.
Wheeled, up to 50,000 lb.	6 to 12
Tracked, up to 100,000 lb.	6 to 12
Wheeled, over 50,000 lb.	9 to 15
Tracked, over 100,000 lb.	9 to 15

In sands, the critical layer is the top 6 inches for all wheeled and tracked vehicles. For most agricultural vehicles, in an area with a normal soil profile (cone indexes increase or remain constant with depth), the critical layer is that between the six and twelve-inch depths.

Other factors that should be considered in evaluating trafficability are land slope and vegetation. Vehicles that can traverse specific soils on level surfaces often become immobilized when climbing slopes on similar soil conditions. This is attributed primarily to a downhill force, a function of the vehicle's weight and the angle of slope, which opposes the vehicle's forward thrust. Vegetation, especially dense grass, if wet with dew or rain, may provide slippery conditions. Soil strength requirements will be greater than normal if small trees or thick brush must be pushed down by the vehicle.

Soil Types and Trafficability Ratings in Wet Season

Moisture content is the principal factor that influences trafficability of a fine-grained soil. Therefore, moisture conditions must be recognized in any evaluation of the trafficability of a soil, and soils must be at similar or equivalent conditions of moisture in order that they may be rated fairly in comparison with each other.

A scheme of classifying soils from the standpoint of their trafficability in the wet season is shown in Table 1 (49). In this table, soils are divided into four general groups from the standpoint of their trafficability during the wet season and rated in the following decreasing order:

Table 1. Trafficability characteristics of soils in wet season (49)

Group	Soils	Unified soil classification system	Probable cone index range
A	Coarse-grained, cohesionless sands and gravels	GW, GP, SW, SP	35 to 100
B	Inorganic clays of high plasticity, fat clays	CH	55 to 165
C	Clayey gravels, gravel-sand-clay mixtures	GC	85 to 175
	Clayey sands, sand-clay mixtures	SC	
	Gravelly clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays	CL	
D	Silty gravels, gravel-sand-silt mixtures	GM	85 to 180
	Silty sands, sand-silt mixtures	SM	
	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	ML and CL-ML	
	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	
	Organic silts and organic silty clays of low plasticity	OL	
	Organic clays of medium to high plasticity, organic silts	OH	

Probable remolding index range	Probable rating cone index range	Slipperiness effects	Stickiness effects
not applicable	not applicable	slight to none	none
0.75 to 1.35	65 to 140	severe to slight	severe to slight
0.45 to 0.75	45 to 125	severe to slight	moderate to slight
0.25 to 0.85	25 to 120	moderate to slight	slight

A, B, C, and D. The soils included in each group are listed in approximate order of their trafficability. Estimates of cone index, remolding index, and rating cone index, slipperiness and stickiness effects for the four soil groups are also shown in this table.

Application of Trafficability Procedures

The ability of a given soil to support the movement of a vehicle is determined by comparing the rating cone index of the soil to the vehicle cone index of the using vehicle. When the rating cone index is equal to or greater than the vehicle cone index, the soil will have sufficient strength to withstand the passage of 50 of the same vehicles (or vehicles with smaller vehicle cone indexes) operating at slow speeds in the same ruts. The strength will also be enough to permit a vehicle to enter the area, stop, back out of the ruts while turning, and retreat from the area. This is the most difficult maneuver from the standpoint of soil strength.

The criteria to assure the passage of a single vehicle across a field is often desirable. Strength criteria for one-pass operation cannot be determined positively. The strength of any soil may vary over a wider range than the strength represented by the difference between a soil condition which will permit only one pass and the condition which will not permit one pass. However, as a general rule a rating cone index equal to 75 percent of the vehicle cone index will be adequate to permit one or two straight-line passes of the vehicle (38). Knight and Freitag (20) reported that the minimum rating cone index required for one pass of an agricultural tractor is 75 percent of the vehicle cone index.

Vehicle performance in fine-grained soils and sands with fines

Several investigators conducted trafficability tests in fine-grained soils and sands with fines. Rush and Temple (34) performed trafficability tests in fine-grained soils with two vehicles with 9 to 10 ton wheel loads. They investigated the effects of heavy wheel loads on soil strength changes under vehicular traffic. Mathews *et al.* (25) studied the relationships between trafficability and geological and engineering properties of silt soils within three areas in Alaska. Bassett *et al.* (1) conducted trafficability studies in four loess soils which were classified as silt loam in the United States Department of Agriculture (USDA) classification system and were representative of loess soils that border much of the Lower Mississippi River.

Freitag (13) tabulated and analyzed wheel performance data from almost 3000 tests which were conducted on two general soil groups that were termed frictional and non-frictional. Rigid-tired and pneumatic-tired wheels were represented. The data were analyzed to show the effects of load, tire geometry, and soil strength on wheel performance. Among the tire geometry variables examined were diameter, width, deflection, carcass construction, and tread pattern. Freitag reported that

> In both soil groups load and soil strength always have an important influence on performance. In frictional soils tire diameter, width, and deflection are very influential while tread pattern and carcass construction are not. In nonfrictional soils tire diameter, width, and deflection have some influence and tread pattern can be very important under particular circumstances. Very little benefit is derived from dual tires and for traction on frictional soils duals are relatively inefficient.

Rush (32) conducted trafficability tests with a two-wheel-drive industrial tractor in a heavy clay soil. The test vehicle was a Model MI (Deere) industrial tractor. He determined the experimental vehicle cone index of the tractor and compared it with the computed value. It was concluded that the performance of the tractor can be related to soil strength in terms of rating cone index.

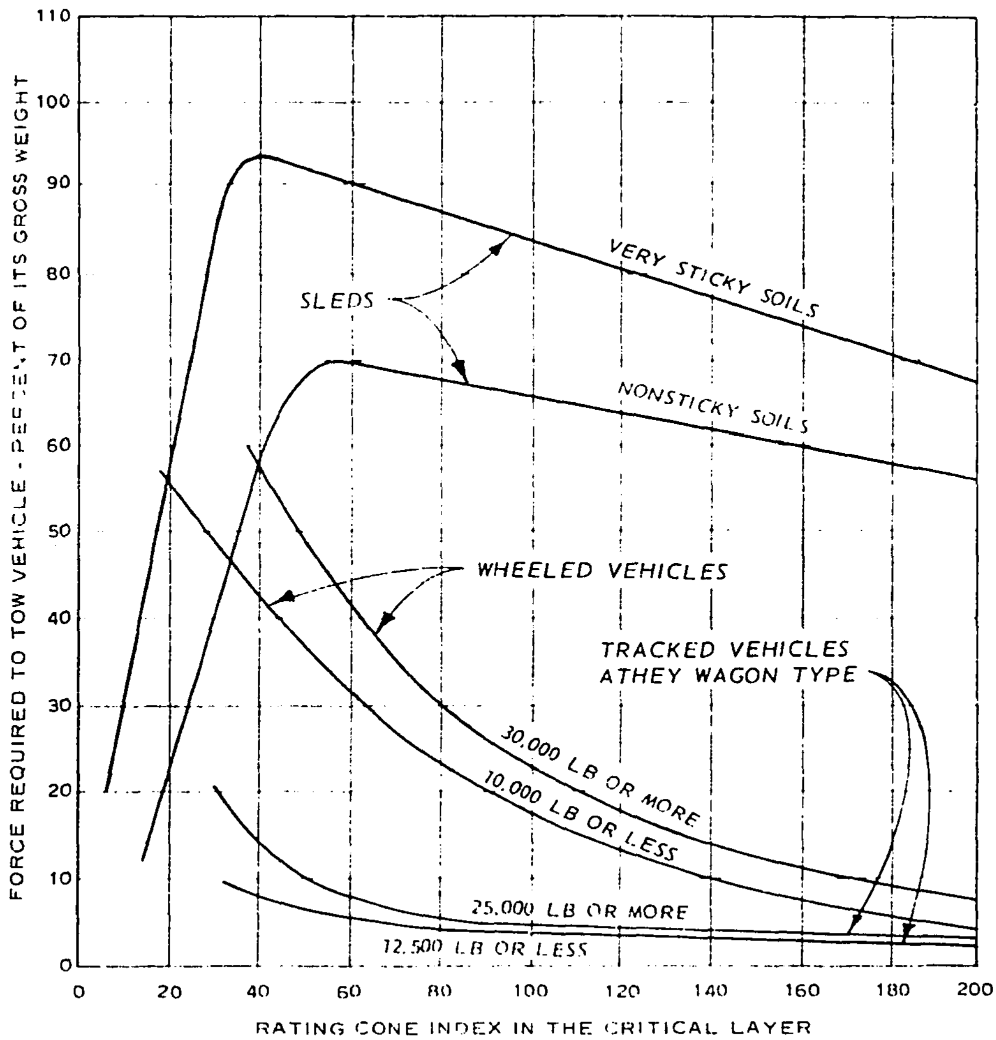
When a vehicle is towing a load, the rating cone index requirements are increased. This is because a vehicle towing a load must overcome not only its own rolling resistance but also that of the towed vehicle. A still greater rating cone index is required to tow loads up slopes. Performance curves for towed vehicles on level terrain are shown in Figure 1 (33). The rating cone index is correlated with required towing force as a percentage of vehicle gross weight for various weights and types of vehicles. If the vehicle and the rating cone index are given, the force required to tow the vehicle on level terrain can be determined. The curves shown in Figure 1 apply only to free-rolling, idle equipment, and not to equipment engaged in tilling or other work that would add to the rolling resistance.

Performance curves for self-propelled vehicles are shown in Figure 2 (38). The rating cone index is related to the maximum towing force that the vehicle can apply on level terrain as a percentage of its gross weight and to the maximum slope the vehicle can negotiate without a towed load. If the vehicle and the required towing force are given, the necessary rating cone index can be determined. If the vehicle and the rating cone index are given, the maximum slope negotiable can be determined.

The maximum slope a vehicle towing another can negotiate can be determined by the following formula (49):

$$\text{Maximum slope in percentage} = \frac{T_1 - T_2}{W_1 + W_2}$$

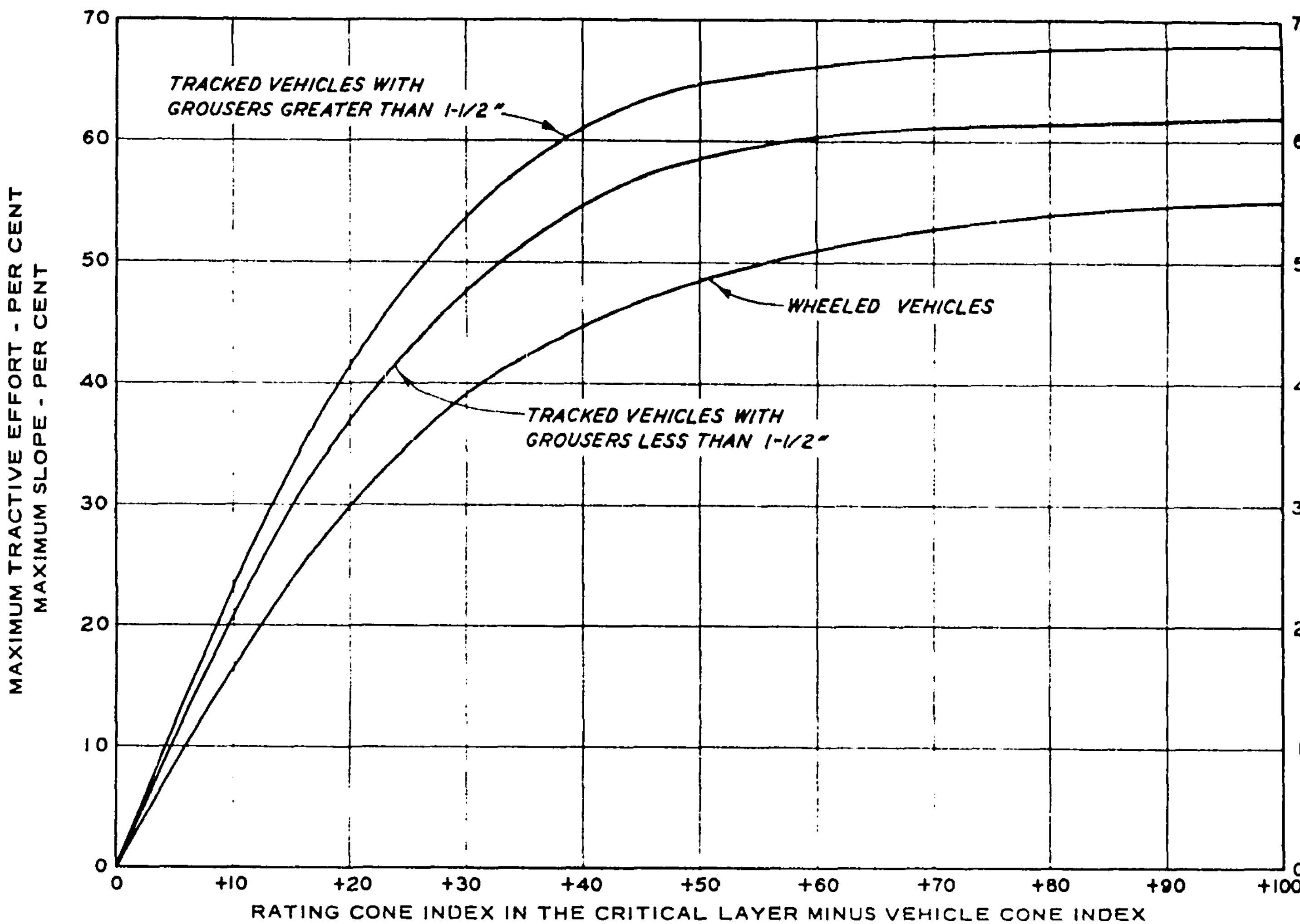
Figure 1. Performance curves for towed vehicles (33)



NOTE: THE TOWING FORCE IN SOFT AREAS WHERE VEHICLES ARE BOGGED DOWN MAY EQUAL OR EXCEED WEIGHT OF VEHICLE.

THESE CRITERIA ALSO APPLY TO SELF-PROPELLED VEHICLES BEING TOWED WITH MOTOR DEAD.

Figure 2. Performance curves for self-propelled vehicles (38)


TRACKED VEHICLES WITH GROUSERS GREATER THAN 1-1/2"
TRACKED VEHICLES WITH GROUSERS LESS THAN 1-1/2"
WHEELED VEHICLES
MAXIMUM TRACTIVE EFFORT - PER CENT
MAXIMUM SLOPE - PER CENT
RATING CONE INDEX IN THE CRITICAL LAYER MINUS VEHICLE CONE INDEX
0
10
20
30
40
50
60
70
+10
+20
+30
+40
+50
+60
+70
+80
+90
+100

Where

T_1 is the maximum tractive power available to the towing vehicle, in pounds,

T_2 is the towing force, in pounds, required on level ground,

W_1 is the weight, in pounds, of the towing vehicle, and

W_2 is the weight, in pounds, of the towed vehicle.

The above equation may have been developed from

$$T_1 - T_2 = (W_1 + W_2) \sin \alpha$$

or

$$\sin \alpha = (T_1 - T_2)/(W_1 + W_2)$$

in which α is the angle of inclination of the sloping plane, and $(W_1 + W_2) \sin \alpha$ is the weight component in the direction of the sloping plane. If α is small, then

$$\sin \alpha = \tan \alpha = \alpha \text{ in radians}$$

It is possible that α was then approximated to a slope in percentage.

<u>Vehicle performance in sands</u>

Sands present far fewer trafficability problems than do fine-grained soils or sand with fines. However, under some conditions, sandy soils can present a serious trafficability problem. The United States Army Engineer Waterways Experiment Station, Corps of Engineers, conducted trafficability tests on coarse-grained soils with self-propelled and towed vehicles (47, 48). Some of the principal conclusions were:

1. The maximum towing force (in percent of weight) of self-propelled wheeled vehicles on level sand was about 2% greater than maximum slope negotiable.

2. The maximum towing force of self-propelled wheeled vehicles is higher on wet-to inundated sands than on dry-to moist sands through the range of cone indexes and tire pressures tested.

3. Vehicle performance on wet sand that tended to liquefy under the vehicle load was similar to that on fine-grained soils.

4. Vehicle performance is better with smooth tires than with treaded tires or traction devices.

Tire pressure significantly affects the performance of a vehicle on sands (38). This can be supported theoretically by use of the Terzaghi bearing capacity equation (37, p. 223):

$$q_{dr} = 1.2\, c\, N_c + \gamma\, D_f\, N_q + 0.6\gamma\, r\, N_\gamma$$

in which

q_{dr} = bearing capacity for circular foundation

c = cohesion of soil

γ = unit weight of soil

D_f = depth of foundation

r = radius of foundation

N_c, N_q, and N_γ = bearing capacity factors

The bearing capacity factors are dimensionless quantities depending only on the angle of internal friction, Ø, of the soil. They can be obtained from a chart given by Terzaghi and Peck (37, p. 222). For vehicles moving on land surface, D_f is negligible. Hence

$$q_{dr} = 1.2\ c\ N_c + 0.6\ \gamma\ r\ N_\gamma$$

For sand c = 0, thus

$$q_{dr} = 0.6\ \gamma\ r\ N_\gamma$$

As tire pressure decreases, r increases, and therefore, q_{dr} increases. For clay Ø = 0, which results in $N_\gamma = 0$ and $N_c = 5.14$; thus

$$q_{dr} = (1.2)\ (5.14)\ c$$

$$= 6.168\ c$$

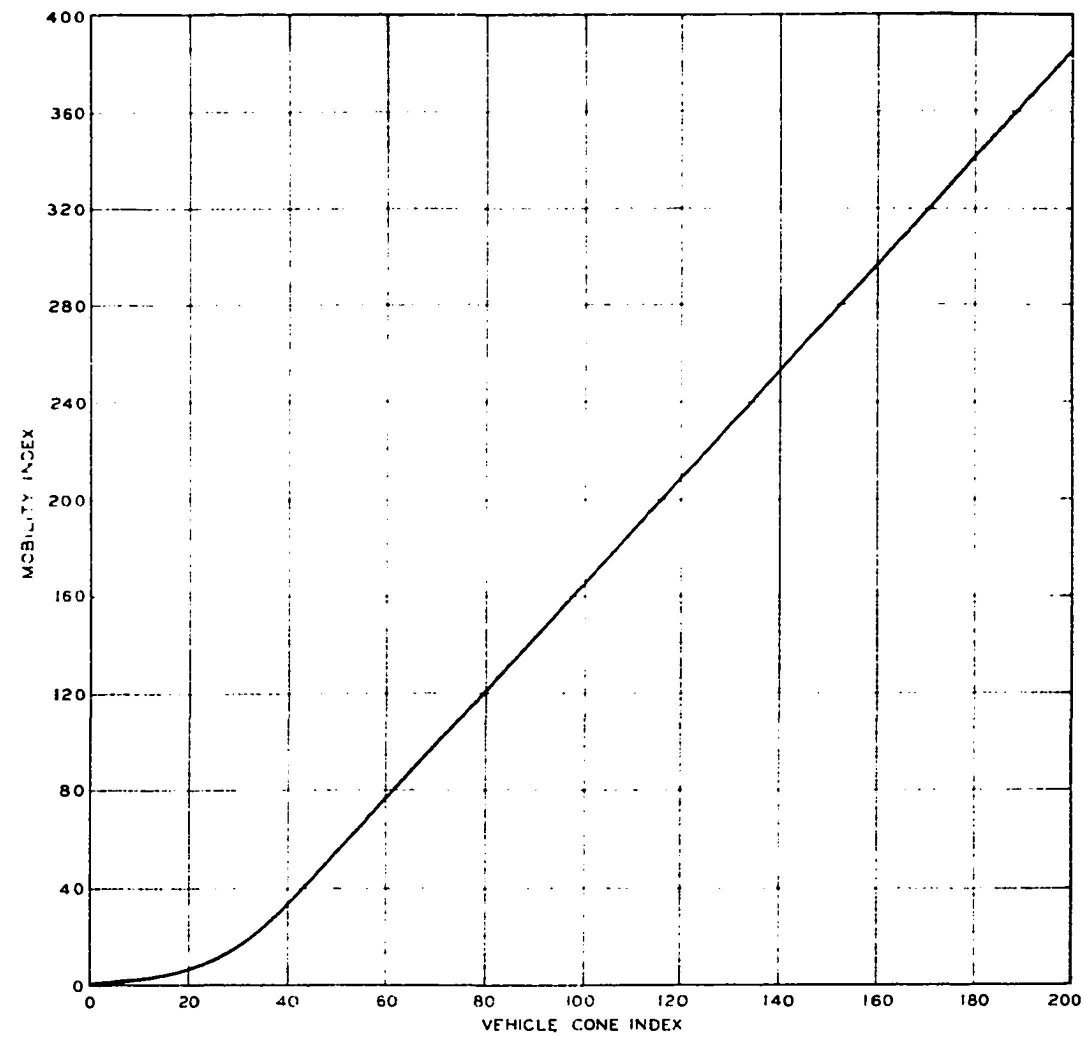
which shows that, for clay, the bearing capacity is a function of cohesion only. Therefore, tire pressure influences the performance of vehicles on sand but not on clay. If a vehicle is equipped with high flotation tires operated at very low pressure (10 to 15 psi), it is considered that the vehicle can negotiate any smooth, level stretch of dry or moist sand (38). However, operation in many very loose dry sands will be critical to driver influence and irregularities in the surface. Slope climbing ability and load towing ability may be determined from the curves shown in Figures 1 and 2.

Classification of vehicles

It was mentioned previously that the ability of a given soil to support the movement of a vehicle is determined by comparing the rating cone index of the soil to the vehicle cone index of the using vehicle. The vehicle cone index is obtained via a mobility index, which results from a consideration of certain vehicle characteristics such as the weight, number of tires, tire width, tire diameter, ground clearance, transmission, and engine horsepower. The mobility index is a dimensionless number obtained for a vehicle operating in fine-grained soils by applying the vehicle characteristics to the formulas given in Appendix A (49). The mobility index can then be applied to the curves shown in Figure 3 to determine the vehicle cone index, which indicates the minimum soil strength in terms of rating cone index required for 50 passes of the vehicle (18).

Vehicles may be divided into four classes: self-propelled tracked vehicles, self-propelled wheeled vehicles, towed tracked vehicles, and towed wheeled vehicles. Appendix A contains the formulas used to determine the mobility index of vehicles falling in any of these four classes.

Figure 3. Mobility index vs. vehicle cone index (18)



NOTE: FOR MI ABOVE APPROXIMATELY 40, VCI CAN BE OBTAINED FROM THE EQUATION VCI = 25.2 + (0.454 X MI).

Mapping of trafficability data

Trafficability data can be placed on maps for greater convenience of use. The four basic factors in describing trafficability are soil type, rating cone index, slope, and slipperiness. Soil type may be shown by a letter symbol (as given in Table 1), rating cone index by a single value, slope by a number indicating ruling grade in percent, and slipperiness by a letter. Slipperiness is rated by the following three categories (44):

Condition	Symbol
1. Not slippery under any condition	N
2. Slippery when wet	P
3. Slippery at all times	S

The four basic factors are presented in fractional form. An example of this form would be $\frac{B-70}{20-P}$, in which B is the soil type (Table 1), 70 is the rating cone index, the ruling grade is 20 percent, and the surface is slippery when wet.

Blank et al. (9) prepared a general trafficability map of Matanuska Valley, Alaska. They reported that in this area cultivated soils provide better trafficability than adjacent virgin tracts of the same soil. The increase in trafficability was attributed to densification of the top soil and better surface drainage.

INSTRUMENTS AND TESTS

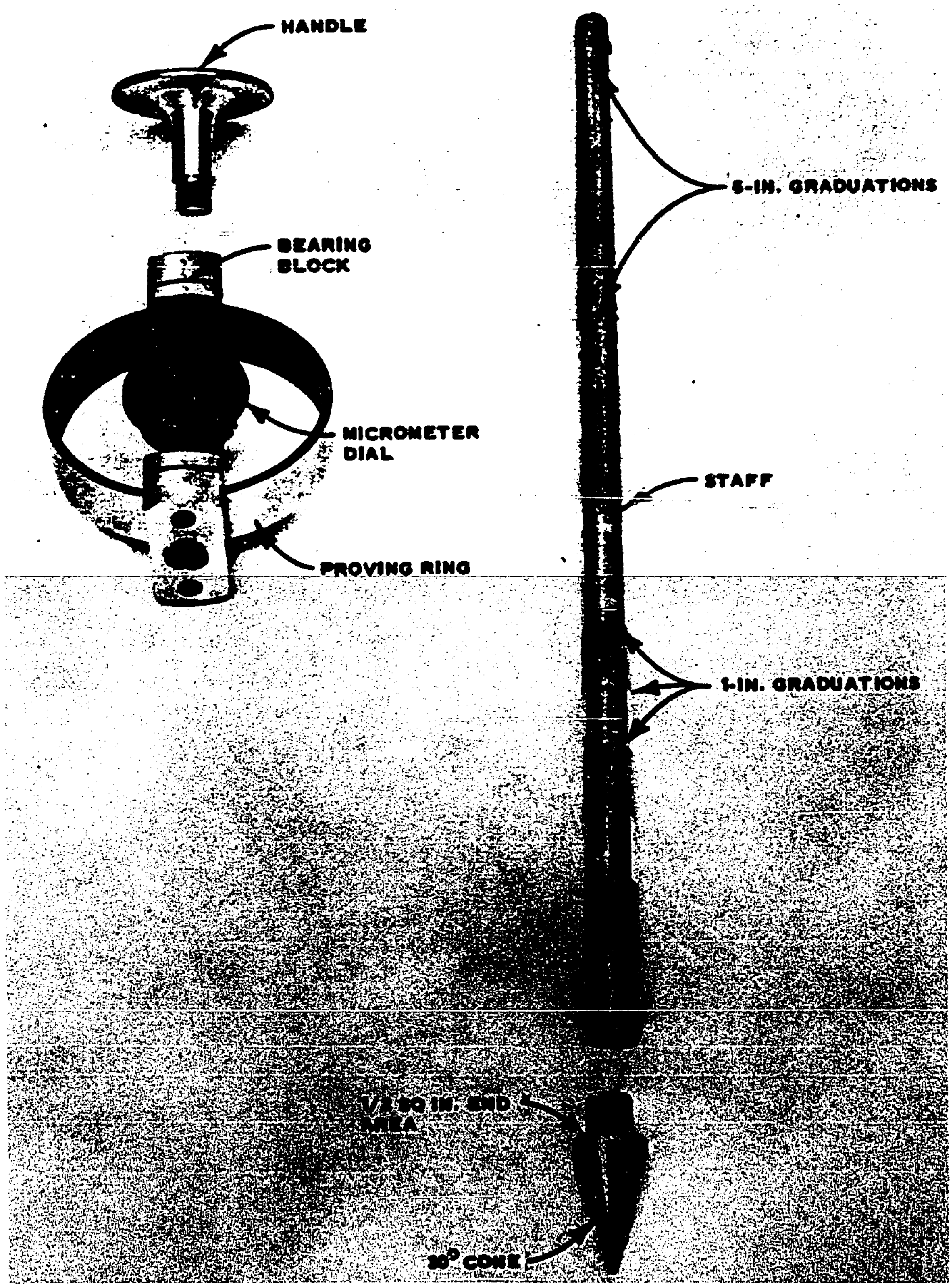
Trafficability measurements are made with the aid of a trafficability soil test set. This set consists of a cone penetrometer, soil sampler, and remolding apparatus.

Cone Penetrometer

The cone penetrometer (Figure 4) is the principal instrument used in evaluating soil trafficability. It consists of a cone, a staff, a proving ring, a micrometer dial, and a handle. The cone, which has a 30 degree apex angle and a base of 1/2 sq. in., is at the bottom. The staff is an aluminum rod, 19 in. long and 5/8 in. in diameter. The lower end of the rod, which has 1-in. graduations, is connected to the cone; the upper end of the rod, which has 6-in. graduations, is connected to the lower bearing block of the proving ring. The proving ring is fitted with a micrometer dial which is graduated from zero to 300. The proving ring and dial are calibrated so that two units on the dial equal one pound of applied force. The upper bearing block of the proving ring is attached to a handle which is shaped to fit the palm of the hand.

When the cone is pushed into the ground, the proving ring is deformed in proportion to the force applied. The

Figure 4. Cone penetrometer (38)


HANDLE
BEARING BLOCK
MICROMETER DIAL
PROVING RING
5-IN. GRADUATIONS
STAFF
1-IN. GRADUATIONS
30° CONE

force required to move the cone slowly through a given plane is indicated in the dial inside the ring. This force is considered to be an index--not an actual measurement--of the shearing resistance of the soil, and is called the cone index of the soil in that plane.

The procedure for using the cone penetrometer is as follows:

1. The dial is zeroed while the instrument is suspended by its hand. If the instrument is kept vertical between the fingertips and allowed to rest on its cone, the dial should register about four, or two pounds, the total weight of the instrument.
2. The apex of the cone is placed on the surface of the ground, so that the staff is vertical.
3. The hands are placed over each other on the handle, palms down and approximately at right angles, as shown in Figure 5, to minimize eccentric loading of the proving ring and to help keep the staff vertical.
4. Force is applied until a steady downward movement occurs.
5. The dial is read as the base of the cone is flush with the ground surface. The steady

Figure 5. Cone penetrometer in use

downward movement is continued and successive dial readings are taken at appropriate intervals, usually at 6-in. intervals.

The recommended rate of penetration for the cone penetrometer is such that four readings (surface, 6, 12, and 18 in.) can be taken in 15 seconds in a continuous penetration. Much slower or faster rates of penetration will yield lower or higher readings, respectively, but the discrepancies will not be large. Effects on cone index of variation in rate of penetration for the same operator or even between experienced operators are insignificant (49). An operator can obtain the "feel" for the proper penetration rate by a little practice using a stop watch.

Soil Sampler

The soil sampler (Figure 6) is a device used to extract undisturbed soil samples for remolding tests. It consists of a sampling tube with a cutting edge, a hollow shaft through which the piston rod slides, a handle, and a disk at the upper end of the piston rod. The locking handle of the sampler locks and unlocks the piston at any position.

To take a sample, the piston is unlocked and the sampler is forced into the ground approximately 6 in. by the handle (Figure 7). In firm soils, two men often are needed to

Figure 6. Soil sampler (38)

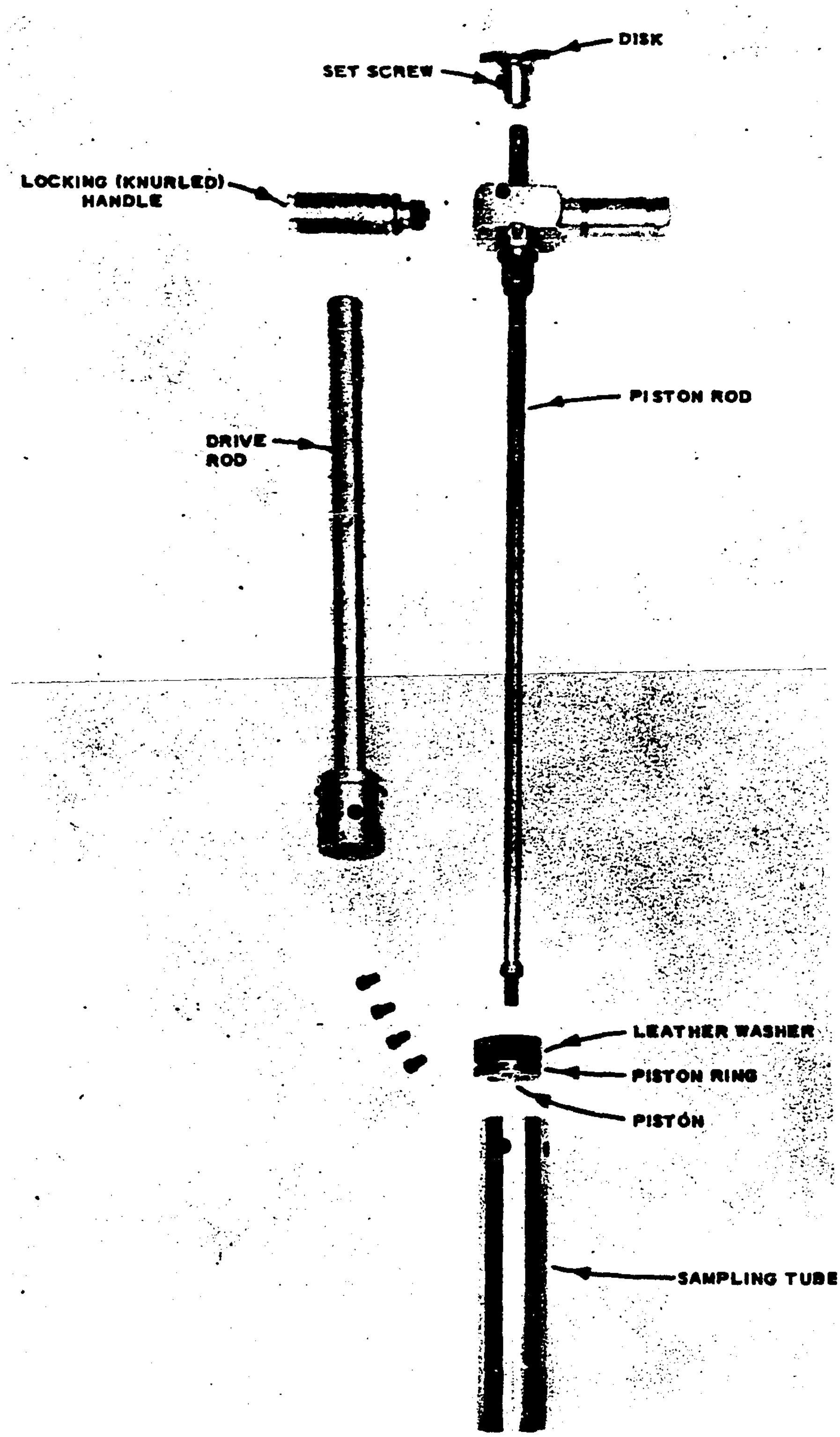
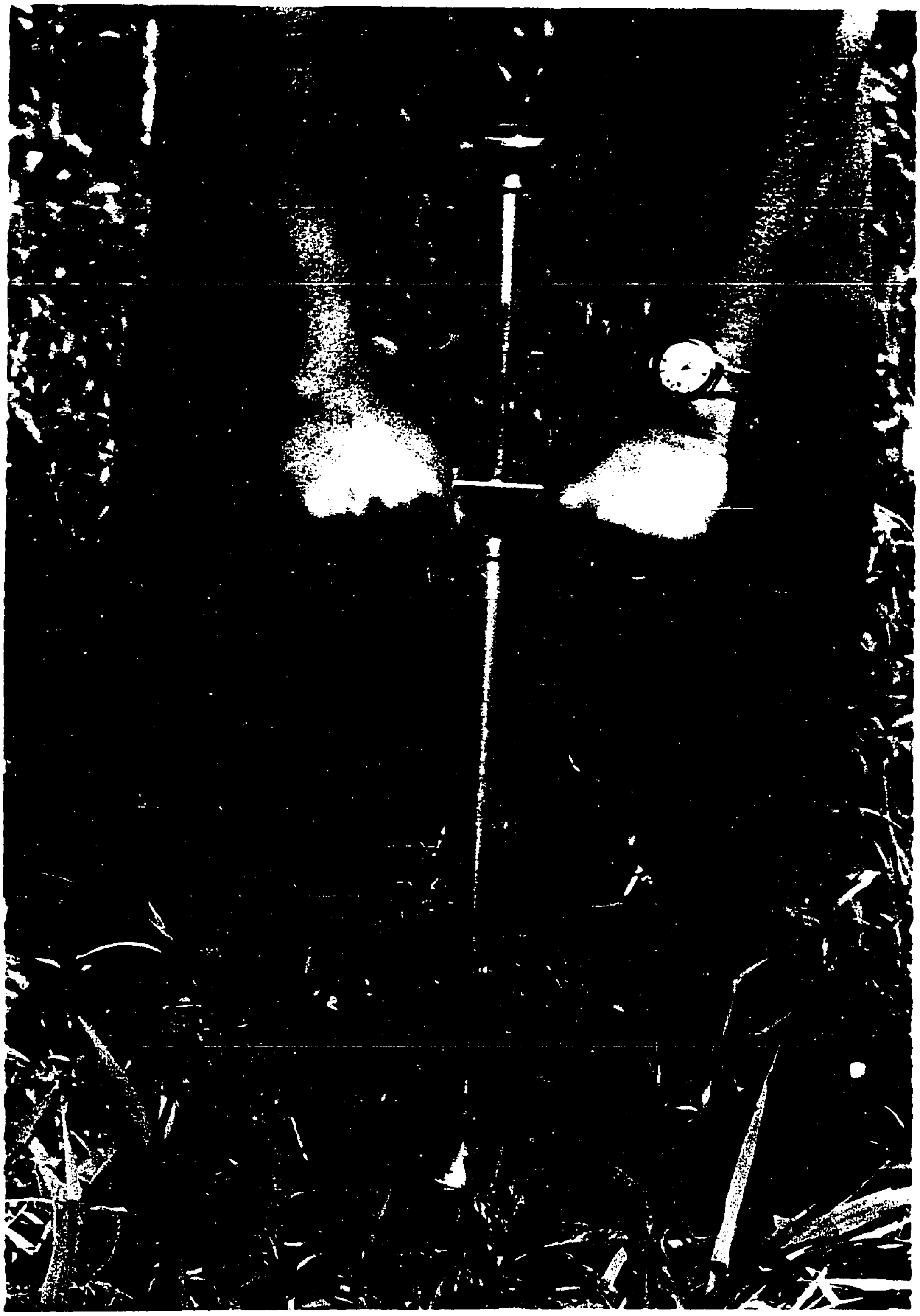

DISK
SET SCREW
LOCKING (KNURLED) HANDLE
PISTON ROD
DRIVE ROD
LEATHER WASHER
PISTON RING
PISTON
SAMPLING TUBE

Figure 7. Soil sampler in use



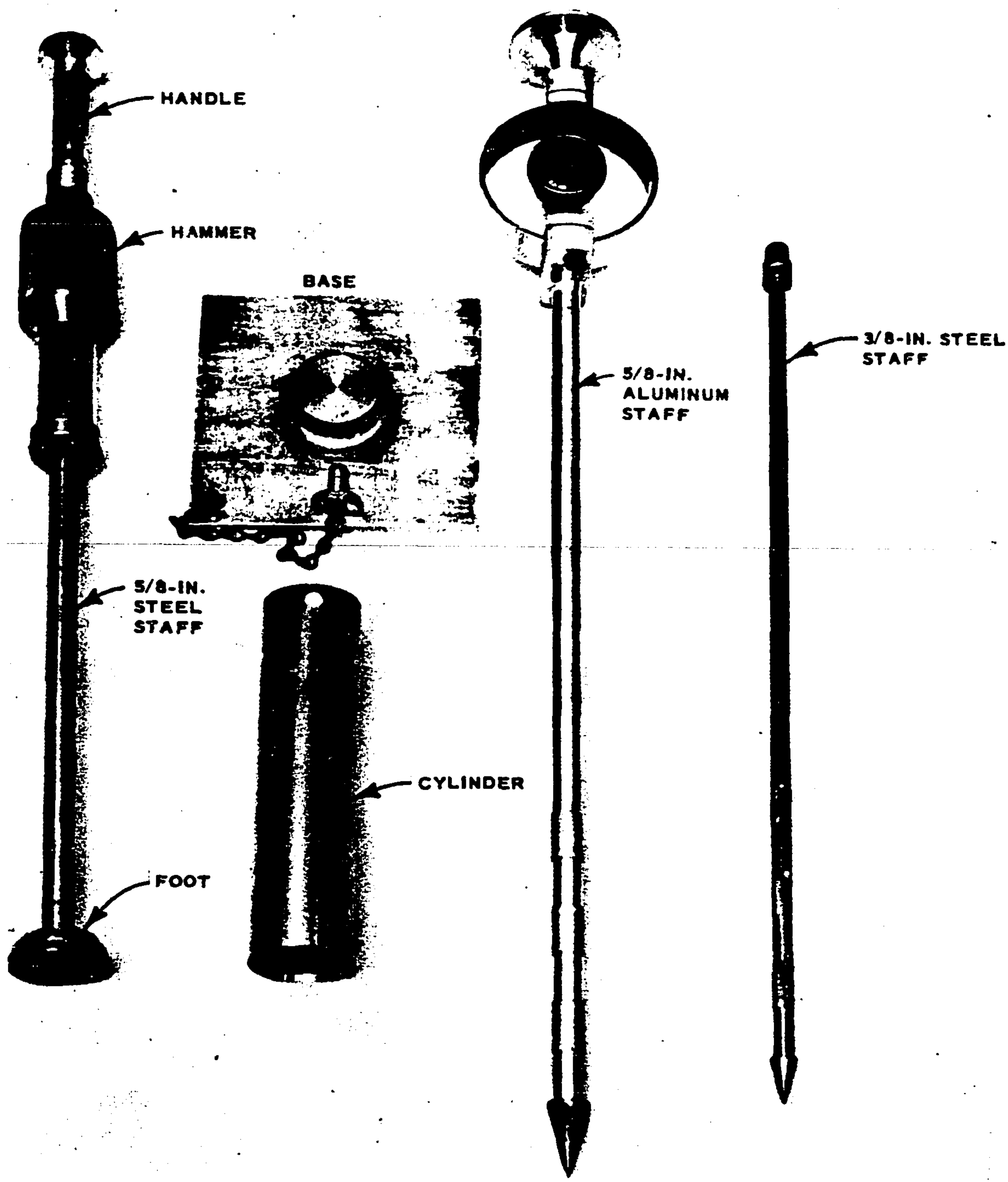
force the sampler into the soil. After locking the piston rod by turning the knurled handle, the sampler is rotated slightly to shear the sample at its bottom and withdrawn from the ground.

It is essential to keep the sampler reasonably clean. The inside of the sampling tube, the piston ring, and the leather washer should be cleaned regularly. If the sampler becomes stiff and hard to work, the tube should be removed, the piston should be disassembled and thoroughly cleaned, and the leather washer should be oiled. The effective piston-rod length must be adjusted to keep the face of the piston flush with the cutting edge of the tube when the piston rod handle (disk) is fully depressed. This may be done by loosening the set screw on the handle, screwing the handle up or down to the correct position, and re-tightening the set screw.

Remolding Apparatus

The remolding apparatus (Figure 8) consists of a hollow cylinder approximately 2 in. in diameter and 8 in. long mounted on a base, a 2 1/2 lb. drop hammer sliding on an 18-in. steel staff with handle, and a cone penetrometer. The cone penetrometer may be equipped with either the aluminum staff with the 0.5 sq. in. cone (for a fine-grained soil)

Figure 8. Remolding test equipment (38)


HANDLE
HAMMER
BASE
5/8-IN.
STEEL
STAFF
CYLINDER
FOOT
5/8-IN.
ALUMINUM
STAFF
3/8-IN. STEEL
STAFF

or the more slender steel staff with the 0.2 sq. in. cone (for a sand with fines).

The remolding test for a fine-grained soil (a soil of which more than 50% of the grains, by weight, will pass a No. 200 sieve) is conducted by first placing the soil sample into the remolding cylinder by the soil sampler (Figure 9). The sample is then gently pushed to the bottom of the cylinder with the drop hammer foot. The strength of the soil sample is measured with the penetrometer (aluminum staff) by taking cone index readings as the base of the cone enters the surface of the soil sample and at each successive inch, to a depth of 4 in. (Figure 10). Next, 100 blows are applied with the drop hammer falling 12 in. (Figure 11), and the remolded strength is measured from the surface to the 4-in. depth at 1 in. intervals, as was done before remolding. The sum of the five cone index readings after remolding, divided by the sum of the five cone index readings before remolding gives the remolding index of the soil.

The remolding test for a sand with fines (a soil which usually contains seven percent or more of material passing No. 200 sieve) is generally the same as that for a fine-grained soil except that the cone index measurements are made with the slender staff and small cone, and the sample is remolded by dropping it (along with cylinder and base) 25 times from a height of 6 in. onto a firm surface.

Figure 9. Loading remolding cylinder

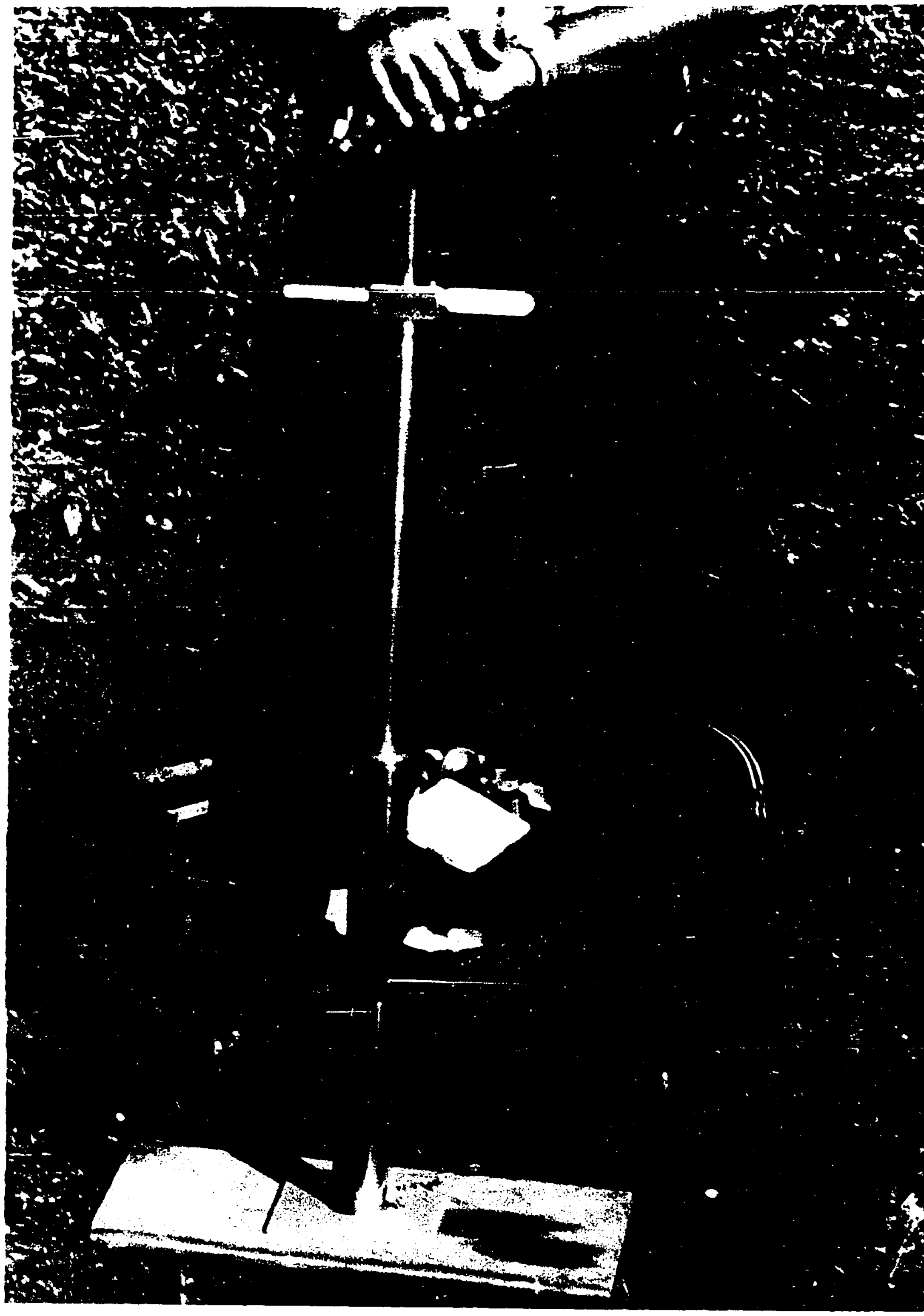


Figure 10. Measuring cone index in remolding cylinder

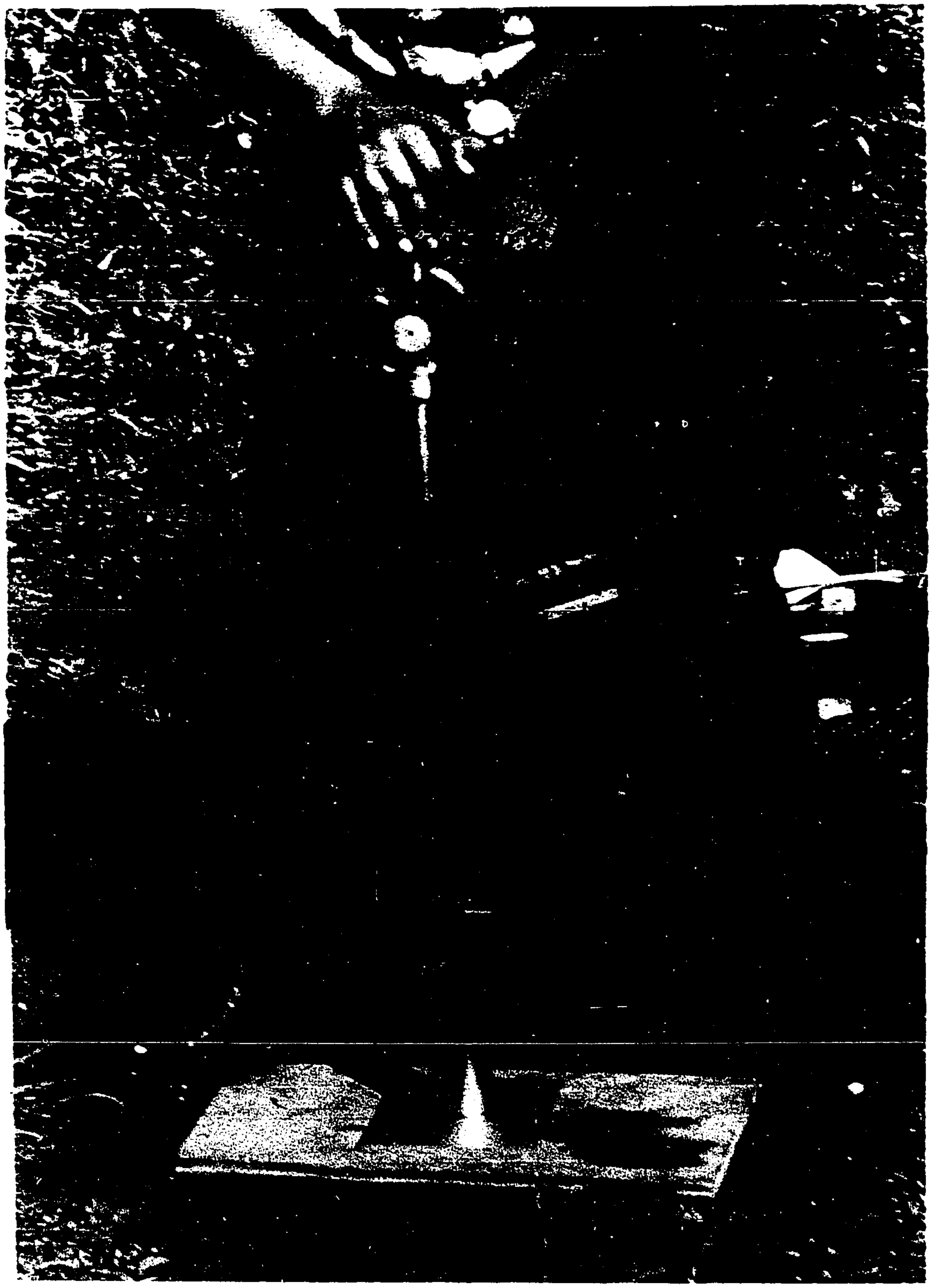


Figure 11. Applying hammer blows

PROCEDURE AND RESULTS

Moisture Content and Water Table Measurements

Measurements of moisture content of soil at the critical layer (6-to 12-in depth) in relation to height of the water table were made in and around two swales; one of them at the Agricultural Engineering Research Farm and the other at the Swine Breeding Farm. These sites were used because (a) they belong to Iowa State University, (b) a high water table existed at these sites during the wet season of 1970, and (c) they are within a reasonable distance from University campus. The soil type of both sites is Webster silty clay loam, a poorly drained soil.

Depths to water table were obtained from auger holes bored with a 2-in. auger. Four auger holes were dug at the Agricultural Engineering Farm and six auger holes were dug at the Swine Breeding Farm. All auger holes were about 4 ft. deep. The first auger hole dug at each farm was near the edge of the water standing in the swale. As the water in each swale receded, other auger holes were dug along a line joining the first auger hole with the center of the swale. The auger holes at the Agricultural Engineering Research Farm were bored at approximately 30 ft. intervals while those at the Swine Breeding Farm were bored at approximately

20 ft. intervals. Each auger hole and the soil surrounding it were considered as a sample area. Therefore, a total of four sample areas were used at the Agricultural Engineering Research Farm and six sample areas were used at the Swine Breeding Farm.

Particle-size analysis and bulk density determination of soil in the critical layer (6- to -12 in. depth) were made for each sample area at the Swine Breeding Farm. The pipette method described by Kilmer and Alexander (19) was used for particle-size analysis. Sodium hexametaphosphate was used to disperse the soil sample, and hydrogen peroxide was used to destroy organic matter. Sedimentation times were taken from the monograph by Tanner and Jackson (36). The 20-50 micron fraction was calculated by subtracting the sum of the other fractions from 100%. Wet sieving was used to determine the fraction larger than 50 microns. The double-cylinder sampler (8) was used for bulk density determination. Results of the particle-size analysis and bulk density determination are shown in Table 2. The liquid limit, plastic limit, and plasticity index of the soil were found to be 45, 33, and 12 respectively.

Moisture content of soil in the critical layer (6- to 12- in. depth) and depth to water table were determined for each sample area at both farms. These determinations were repeated every 2 to 7 days. Table 3 shows depth to water

Table 2. Particle-size analysis and density of soil for Swine Breeding Farm

Sample area	Sand % 2000-50 micron	Coarse silt % 50-20 micron	Fine silt % 20-2 micron	Clay % <2 micron	Bulk density gm/cm^3
1	25.83	21.00	25.39	27.78	1.29
2	25.65	20.60	23.25	30.50	1.26
3	14.86	21.35	28.15	35.64	1.17
4	13.60	20.10	29.89	36.41	1.15
5	9.80	19.77	32.40	38.03	1.12
6	11.40	18.13	32.85	37.62	1.15

Table 3. Moisture content at 6- to 12-in. depth with varying depths to water table for Agricultural Engineering Research Farm

Sample area	Measurement number	Depth to water table in.	Moisture content[a] %
1	1	21	30.46
	2	27	27.14
	3	29	28.03
	4	30	27.39
	5	31	26.93
	6	32	24.18
2	1	14	29.18
	2	17	27.42
	3	21	26.14
	4	22	26.43
	5	25	24.64
	6	26	24.98
3	1	14	32.41
	2	19	32.14
	3	20	32.08
	4	22	30.33
	5	24	29.22
	6	25	30.63
4	1	15	36.69
	2	16	36.09
	3	21	32.00
	4	22	30.27
	5	23	28.51
	6	24	27.04

[a]Average of two values.

table and moisture content values obtained at the Agricultural Engineering Farm. The third and fourth columns of Table 4 show values of depth to water table and moisture content, respectively, obtained at the Swine Breeding Farm.

Soil Strength Measurements

Soil strength measurements in terms of cone index and remolding index were made at the Swine Breeding Farm. The cone index of the soil in each sample area was measured at the surface and at 6-in. vertical increments to a depth of 18 in. using the cone penetrometer. The remolding index of the soil in the critical layer (6- to 12-in. depth) of each sample area was determined using the soil sampler and the remolding apparatus. Values of cone index and remolding index obtained at the Swine Breeding Farm are shown in Table 4. These values were obtained at the same time that values of moisture content and depth to water table were obtained.

Laboratory Tests

Laboratory tests were conducted to develop relationships between soil strength and moisture content. Soil for these tests was obtained from the sixth sample area of the

Table 4. Values of water table, moisture content, cone index, remolding index, and rating cone index for Swine Breeding Farm

Sample area	Measurement number	Depth to water table in.	Moisture content[a] %	Degree of saturation %
1	1	21.0	33.62	83.05
	2	23.0	30.10	74.35
	3	25.0	29.83	73.69
	4	27.5	32.85	81.15
	5	36.5	23.86	58.94
	6	37.5	28.98	71.59
	7	38.0	25.06	61.90
2	1	17.0	35.93	84.88
	2	19.0	37.68	89.02
	3	20.0	33.34	78.77
	4	21.5	31.28	73.90
	5	29.5	30.93	73.07
	6	33.0	32.27	76.24
	7	35.0	31.18	73.66
3	1	4.0	44.28	91.43
	2	8.5	45.61	94.17
	3	17.0	34.27	70.76
	4	20.5	34.04	70.28
	5	23.5	34.50	71.23
	6	30.0	32.81	67.74
	7	31.5	33.67	69.52

[a]Average of two values.

Table 4. (Continued)

Sample area	Cone index[b] at depth of 0 in.	6 in.	12 in.	18 in.	Cone index 6 in.-12 in.	Remolding index	Rating cone index
1	52	94	113	116	103	0.84	87
	67	113	113	87	113	0.83	94
	45	120	97	102	108	0.88	95
	50	127	117	80	122	0.90	110
	70	210	148	153	179	0.96	172
	88	197	133	127	165	1.02	168
	62	190	160	117	175	1.06	185
2	76	95	96	115	95	0.90	85
	50	108	113	115	110	0.83	91
	50	110	100	110	105	0.86	90
	50	127	90	90	108	0.90	97
	43	143	113	100	128	0.96	123
	60	167	143	145	155	1.02	158
	63	180	127	115	153	1.04	159
3	7	66	106	130	86	0.63	54
	18	61	107	152	84	0.69	58
	39	90	101	120	95	0.90	85
	30	93	92	103	92	0.90	83
	42	105	111	114	108	0.96	104
	77	117	120	110	118	1.00	118
	47	135	110	117	122	1.02	124

[b]Average of three values.

Table 4. (Continued)

Sample area	Measurement number	Depth to water table in.	Moisture content %	Degree of saturation %
4	1	13.0	45.24	90.63
	2	15.0	36.30	72.72
	3	15.5	35.87	71.86
	4	17.5	41.29	82.71
	5	27.5	36.24	72.60
	6	28.5	35.21	70.53
	7	29.0	32.83	65.77
5	1	12.0	40.38	77.28
	2	13.0	42.86	82.03
	3	16.0	36.45	69.76
	4	18.0	36.25	69.38
	5	27.0	36.51	69.88
	6	28.0	31.14	59.60
	7	28.5	31.41	60.12
6	1	12.0	42.09	84.32
	2	14.0	38.89	77.91
	3	15.0	36.03	72.18
	4	16.5	38.49	77.10
	5	25.5	34.05	68.21
	6	26.5	33.51	67.13
	7	27.0	34.42	68.95

Table 4. (Continued)

Sample area	Cone index at depth of 0 in.	6 in.	12 in.	18 in.	Cone index 6 in.-12 in.	Remolding index	Rating cone index
4	8	77	89	103	83	0.70	58
	51	82	93	110	87	0.80	70
	30	70	100	107	85	0.84	71
	37	102	85	103	93	0.77	72
	45	97	103	102	100	0.86	86
	50	103	107	97	105	0.87	91
	77	107	98	98	102	0.85	87
5	8	58	85	93	71	0.70	50
	27	60	113	157	86	0.70	60
	37	65	113	133	39	0.80	71
	57	72	93	112	82	0.77	63
	57	87	95	97	91	0.84	76
	113	107	100	95	103	0.87	90
	80	83	105	100	94	0.85	80
6	15	57	83	123	70	0.70	49
	17	50	97	143	73	0.80	58
	30	57	97	113	77	0.80	62
	18	38	83	117	60	0.77	46
	130	97	102	112	99	0.82	81
	117	67	90	103	78	0.87	68
	63	98	98	97	98	0.85	83

Swine Breeding Farm. The soil was placed in two large barrels and compacted in 6-in. layers to obtain a soil density approximately equal to the field density. Cone index of the critical layer, which is the average value of the 6-in. depth and 12-in. depth penetrometer readings, and moisture content of soil in the critical layer were determined for each barrel. These determinations were repeated every 2 to 5 days.

Since the process of placing a wet fine-grained soil in a barrel and compacting it has similar effect to that of the remolding test, it was assumed that the two processes are analogous. Therefore, values of rating cone index were considered to be equal to values of cone index. Table 5 shows average values of moisture content and rating cone index from laboratory tests.

Determination of Vehicle Cone Index of Some Agricultural Tractors

Vehicle characteristics, vehicle cone index for fifty passes, and vehicle cone index for one pass of some agricultural tractors are shown in Appendix B. The vehicle cone index for fifty passes was found by first determining the mobility index, then converting the mobility index to vehicle cone index. The mobility index was determined by

Table 5. Average values of moisture content and rating cone index from laboratory tests

Barrel number	Measurement number	Moisture content[a] %	Rating cone index[b]
1	1	44.65	47
	2	43.22	48
	3	39.38	60
	4	38.67	66
	5	37.71	70
	6	35.58	84
	7	34.02	89
	8	33.26	85
2	1	40.61	52
	2	39.94	61
	3	38.92	66
	4	38.32	56
	5	36.07	82
	6	35.05	69
	7	34.25	86
	8	33.18	86

[a]Average of two values.

[b]Average of three values.

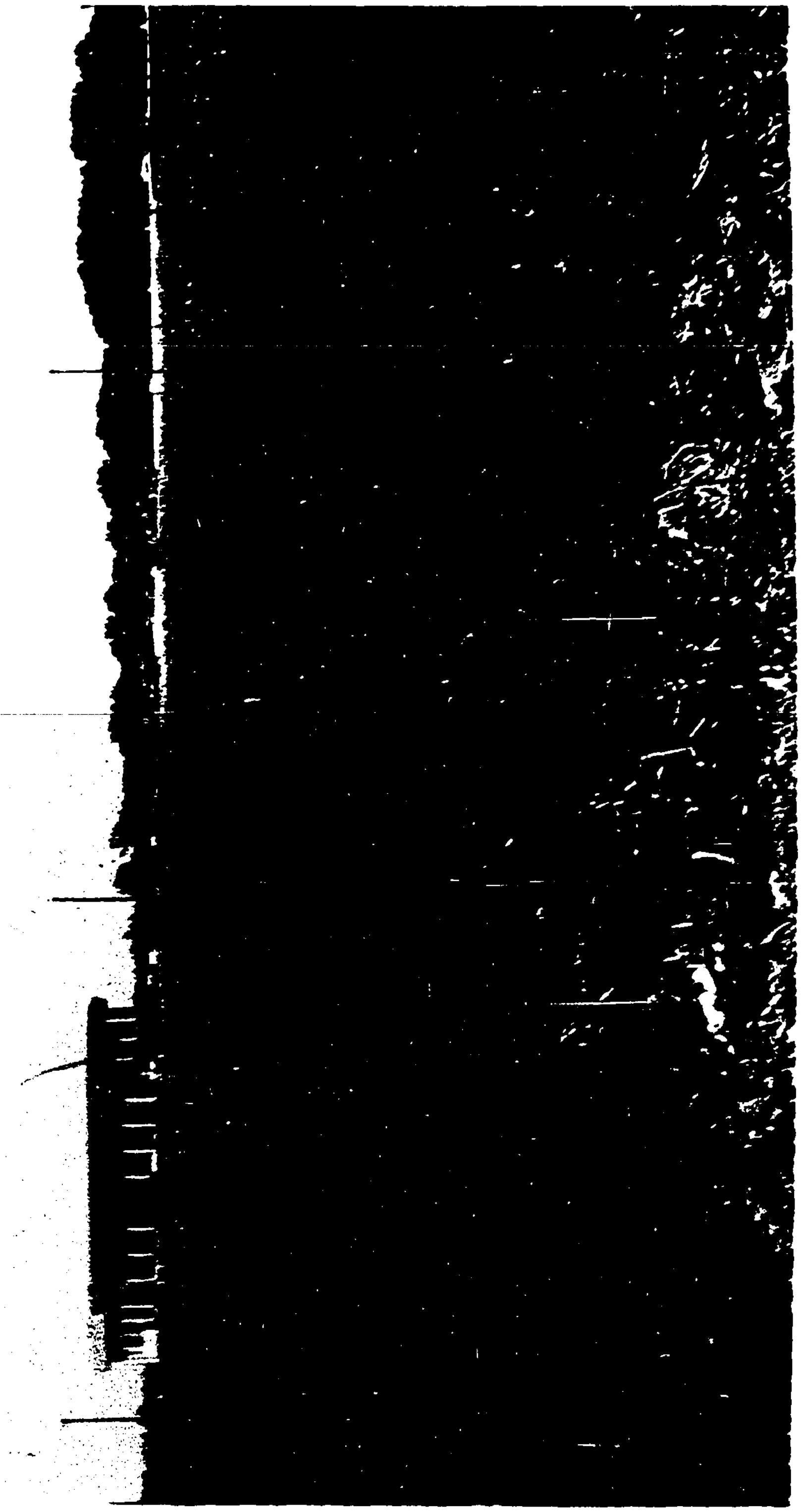
applying vehicle characteristics in the formulas given in Appendix A. The mobility index was then applied to the curve shown in Figure 3 to determine the vehicle cone index, which indicates the minimum soil strength in terms of rating cone index required for fifty passes of the vehicle. Vehicle cone index for one pass of the vehicle was determined by taking 75 percent of the vehicle cone index for fifty passes of the vehicle.

Tractor Tests

Tractor tests were performed with a Ford 3000, 8 speed, gasoline tractor. The characteristics, vehicle cone index for fifty passes, and vehicle cone index for one pass of the tractor are given in Appendix B.

The site for the tests (Figure 12) was on the Iowa State University experiment fields located between Beach Avenue and South Riverside Drive at Ames, Iowa. The soil on this site is a Colo clay loam. Its liquid limit, plastic limit, and pasticity index are 46, 30, and 16 respectively. At a depth from 5 to 6 ft., sand or gravel is usually encountered. The soil, therefore, has a good internal drainage.

Figure 12. Site used for tractor tests



A sprinkler system was set up to saturate the upper 2 to 3 ft. of the soil. Water was kept running in the system 16 hours a day for a period of 3 days.

Three tractor tests were conducted by driving the vehicle in a 100-ft.-long test lane (a new lane was used for each test) to observe the behavior of the soil and of the vehicle and to see if there are any signs of immobilization. At the beginning of each test, the 100-ft.-long test lane was staked out and the cone index of the soil was measured at 10-ft. stations along the expected paths of both wheels of the vehicle. The cone index measurements were made at the surface and at 6-in. vertical increments to a depth of 18 in. Remolding index was determined on soil samples taken near the stations where the lowest cone index was measured in each path. Soil samples for particle-size analysis, moisture content determination, and density determination were also taken at these stations. The first pass of the vehicle was made and no signs of immobilization were noticed. Figure 13 shows the vehicle making its first pass in one of the test lanes without any difficulty except stickiness. The problem of stickiness can be seen clearly in Figure 14. The second pass of the vehicle was then made (Figure 15) and, again, no signs of immobilization were noticed. Figure 16 shows the ruts after the second pass. Rut depth was measured from the ground surface after the

Figure 13. Tractor making a first pass

Figure 14. Problem of stickiness

Figure 15. Tractor making a second pass

Figure 16. Ruts after the second pass

second pass at 10-ft. stations along each path. Tables 6, 7, and 8 show values of cone index and rut depth that were obtained from test lanes 1, 2, and 3 respectively. Values of moisture content and remolding index that were determined from soil samples taken near the stations where the lowest cone index was measured in each path are given in Table 9. Particle-size analysis and bulk density of soil samples taken at these stations are shown in Table 10.

Table 6. Values of cone index and rut depth for tractor test lane 1

Station	Cone index at depth of 0 in.		6 in.		12 in.		18 in.		Cone index at 6-12 in.		Rut depth after 2 passes, in.	
	L[a]	R[b]	L	R	L	R	L	R	L	R	L	R
0+00	10	5	100	130	220	160	220	220	160	145	3.5	3.0
0+10	5	5	160	80	200	160	200	215	180	120	3.0	3.5
0+20	5	10	160	130	240	180	180	180	200	155	3.5	3.0
0+30	5	6	170	70	200	130	180	200	185	100	2.5	2.5
0+40	10	5	150	50	140	190	160	200	145	120	4.5	3.0
0+50	15	5	150	90	140	105	170	130	145	97	4.0	4.0
0+60	10	10	130	50	180	135	230	185	155	92	3.5	4.0
0+70	10	10	140	130	160	200	200	220	150	165	4.0	4.5
0+80	5	15	165	140	185	170	190	200	175	155	4.0	4.0
0+90	40	20	160	65	180	200	215	225	170	132	4.0	4.0
1+00	50	10	165	60	160	130	200	180	162	95	4.0	4.0
Ave.	15	9	150	90	182	160	195	196	166	125	3.8	3.7

[a] L means left-wheel path.

[b] R means right-wheel path.

Table 7. Values of cone index and rut depth for tractor test lane 2

Station	Cone index at depth of								Cone index at 6-12 in.		Rut depth after 2 passes, in.	
	0 in.		6 in.		12 in.		18 in.					
	L[a]	R[b]	L	R	L	R	L	R	L	R	L	R
0+00	5	5	80	130	160	160	180	200	120	145	3.5	3.5
0+10	10	15	120	60	190	100	205	180	155	80	4.0	4.0
0+20	5	5	170	60	165	150	220	180	167	105	4.5	3.5
0+30	10	5	70	80	150	140	215	160	110	110	3.0	3.5
0+40	20	10	80	65	140	180	200	220	110	122	4.0	4.0
0+50	5	5	160	90	160	155	205	180	160	122	3.0	4.5
0+60	5	5	160	90	150	160	190	200	155	125	3.5	4.5
0+70	5	5	50	100	170	165	190	180	110	132	4.0	4.0
0+80	10	5	65	60	170	170	180	200	117	115	4.5	5.0
0+90	5	5	60	70	150	150	185	160	105	110	4.0	4.0
1+00	5	10	40	80	150	140	160	160	95	110	5.0	3.5
Ave.	8	7	96	80	160	152	194	184	128	116	3.9	4.0

[a]L means left-wheel path.

[b]R means right-wheel path.

Table 8. Values of cone index and rut depth for tractor test lane 3

Station	Cone index at depth of 0 in. L[a]	R[b]	6 in. L	R	12 in. L	R	18 in. L	R	Cone index at 6-12 in. L	R	Rut depth after 2 passes, in. L	R
0+00	8	15	105	160	160	200	170	210	132	180	3.5	3.0
0+10	5	5	100	70	160	160	210	220	130	115	4.0	4.0
0+20	20	10	60	100	160	170	175	205	110	135	4.0	4.0
0+30	10	10	200	60	160	80	220	200	180	70	3.5	4.5
0+40	10	10	150	60	120	110	180	215	135	85	4.0	4.0
0+50	30	10	100	140	160	180	220	220	130	160	4.0	3.5
0+60	10	5	70	80	150	130	180	200	110	105	4.5	4.5
0+70	5	10	70	100	165	140	220	240	117	120	4.5	5.0
0+80	5	5	120	100	160	105	210	180	140	102	4.5	4.5
0+90	5	10	40	40	150	120	220	180	95	80	4.0	4.0
1+00	20	20	40	90	120	180	190	230	80	135	4.0	4.0
Ave.	12	10	96	91	151	143	200	209	124	117	4.0	4.1

[a] L means left-wheel path.

[b] R means right-wheel path.

Table 9. Values of moisture content, remolding index, and rating cone index at stations of lowest cone index in each tractor path

Test lane	Path	Station	Moisture content %	Remolding index	Rating cone index
1	L[a]	0+50	31.08	0.95	138
	R[b]	0+60	31.14	0.94	86
2	L	1+00	33.27	0.88	84
	R	0+10	35.64	0.85	68
3	L	1+00	35.82	0.82	66
	R	0+30	36.76	0.81	57

[a]L means left-wheel path.

[b]R means right-wheel path.

Table 10. Particle-size analysis and bulk density of soil at stations of lowest cone index in each tractor path

Test lane	Path	Station	Sand % 2000-50 micron	Coarse silt % 50-20 micron	Fine silt % 20-2 micron	Clay % <2 micron	Bulk density gm/cm^3
1	L[a]	0+50	14.15	15.98	28.96	40.91	1.37
	R[b]	0+60	14.48	15.50	29.28	40.74	1.30
2	L	1+00	12.71	15.08	29.00	43.21	1.24
	R	0+10	14.28	16.47	28.55	40.70	1.23
3	L	1+00	12.38	15.17	32.76	39.69	1.27
	R	0+30	13.43	15.05	28.71	42.81	1.28

[a]L means left-wheel path.

[b]R means right-wheel path.

ANALYSIS OF DATA

Relations Between Soil Moisture Content and Depth to Water Table

Values of moisture content of soil in the critical layer (6- to 12-in. depth) and depth to water table that were obtained at the Agricultural Engineering Research Farm and the Swine Breeding Farm were tabulated in Tables 3 and 4 respectively. These values were analyzed to derive linear regression lines relating soil moisture content to depth to water table. Figures 17 and 18 show moisture content plotted versus depth to water table for Agricultural Engineering Research Farm and Swine Breeding Farm respectively. The regression lines shown in these Figures were obtained by the method of least squares. The regression equations for the lines shown in Figures 17 and 18 are, respectively:

$$MC = 38.79 - 0.43\ DWT \qquad (1)$$

and

$$MC = 46.09 - 0.49\ DWT \qquad (2)$$

where

MC = moisture content

DWT = depth to water table

The correlation coefficients between soil moisture content and depth to water table for the Agricultural Engineering

Figure 17. Soil moisture content versus depth to water table for Agricultural Engineering Research Farm

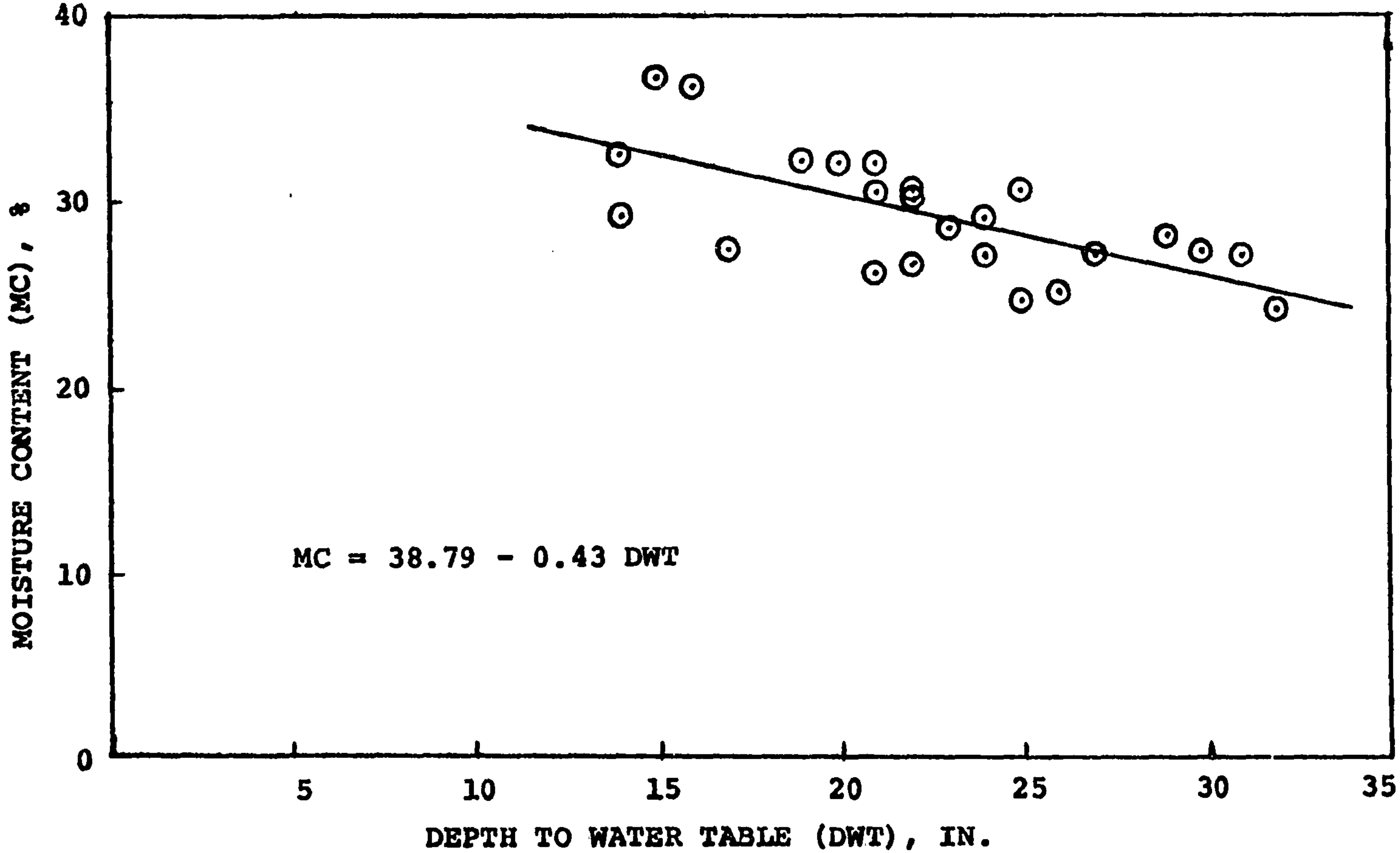
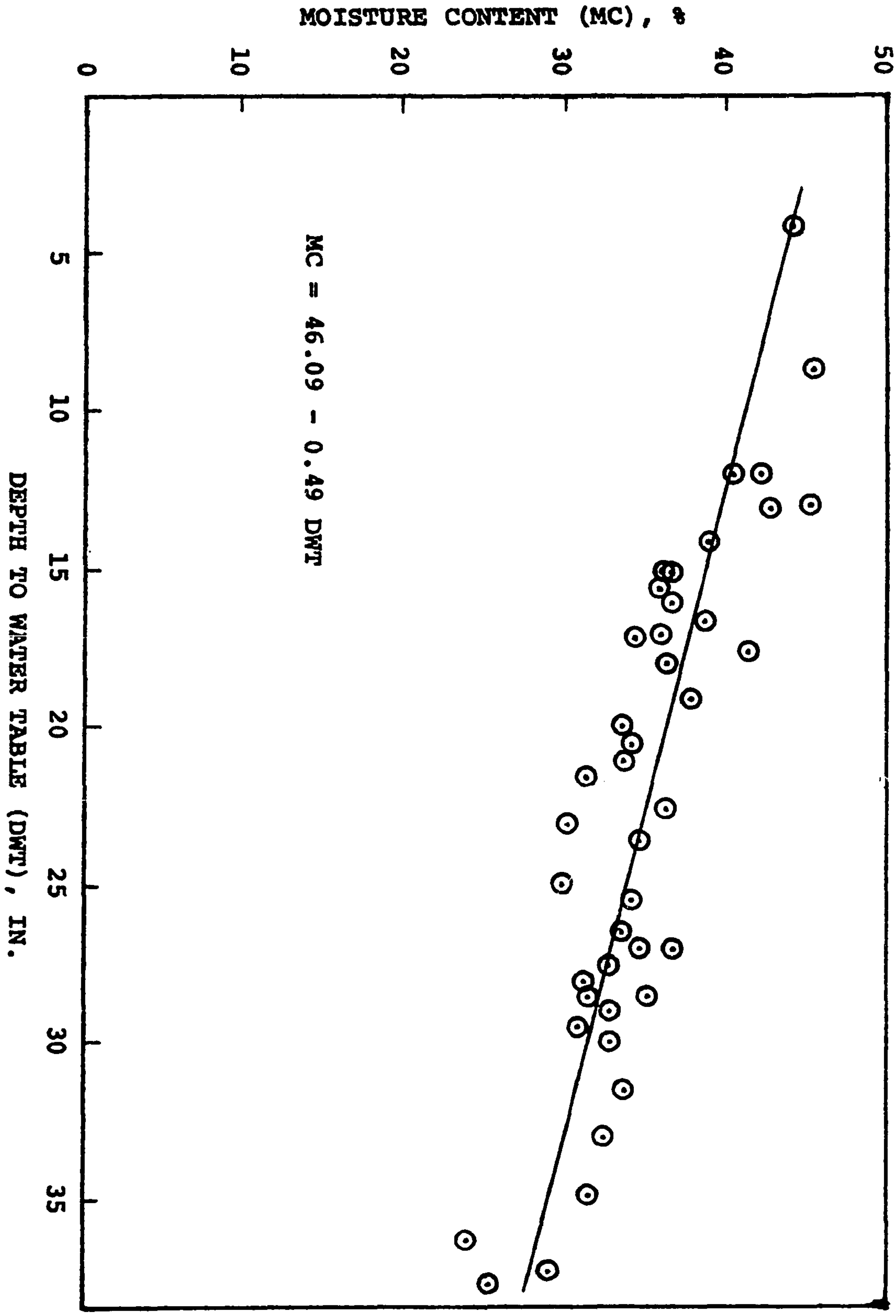

40
30
20
10
0
5
10
15
20
25
30
35
MOISTURE CONTENT (MC), %
DEPTH TO WATER TABLE (DWT), IN.
MC = 38.79 - 0.43 DWT

Figure 18. Soil moisture content versus depth to water table for Swine Breeding Farm


MOISTURE CONTENT (MC), %
0
10
20
30
40
50
5
10
15
20
25
30
35
MC = 46.09 - 0.49 DWT
DEPTH TO WATER TABLE (DWT), IN.

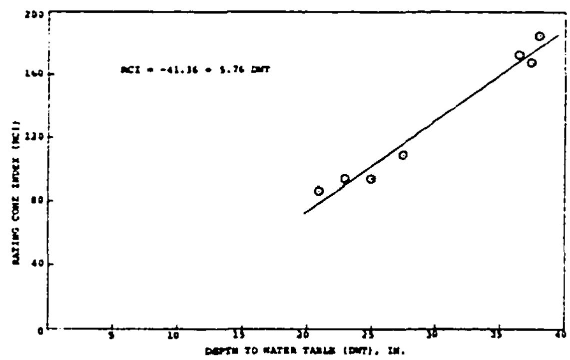
Research Farm and the Swine Breeding Farm were -0.670 and -0.841 respectively. The negative sign means that the moisture content decreases as the depth to water table increases. Both correlation coefficients are significant at 0.01 level.

Relations Between Soil Strength and Depth to Water Table

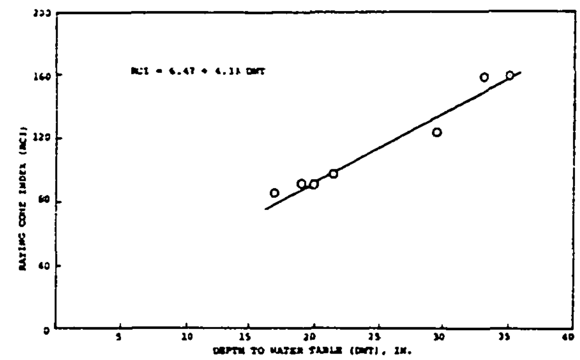
Values of cone index, remolding index, and depth to water table that were obtained at the Swine Breeding Farm were tabulated in Table 4. Cone index at the critical layer was determined by averaging the cone index values at the 6-in. and 12-in. depths. Rating cone index was found by multiplying the cone index at the critical layer by the remolding index. Values of cone index at the critical layer and rating cone index are shown in Table 4.

Values of rating cone index and depth to water table were analyzed to derive linear regression lines relating rating cone index to depth to water table. Figure 19 shows rating cone index plotted versus depth to water table for each sample area of the Swine Breeding Farm. Table 11 shows regression equation, correlation coefficient, and level of significance for each regression line.

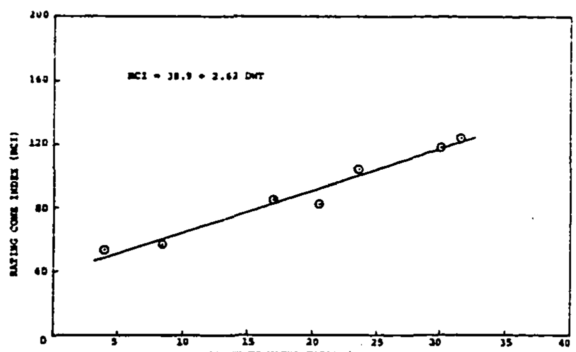
Figure 19. Rating cone index versus depth to water table for Swine Breeding Farm



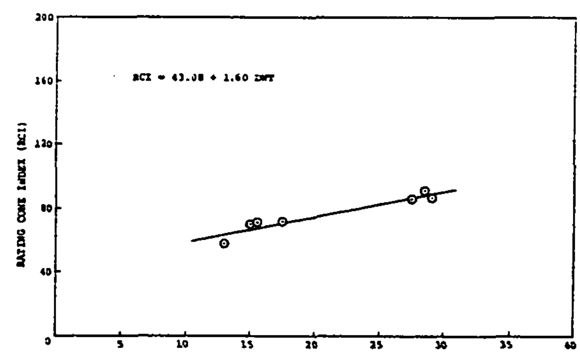
SAMPLE AREA 1



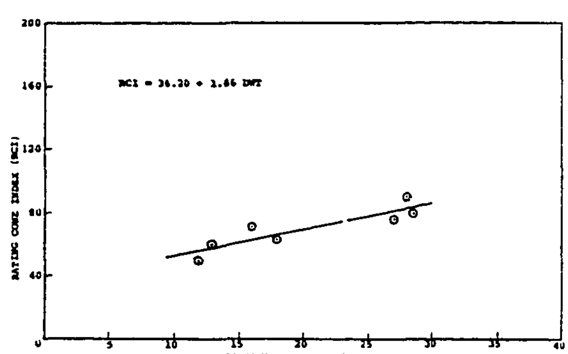
SAMPLE AREA 2



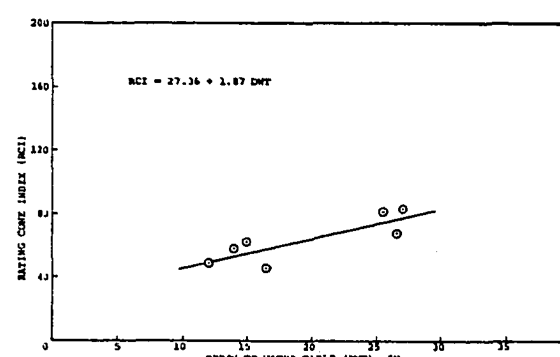
SAMPLE AREA 3



SAMPLE AREA 4



SAMPLE AREA 5



SAMPLE AREA 6

Table 11. Soil strength related to depth to water table at Swine Breeding Farm

Sample area	Regression equation	Correlation coefficient	Level of significance
1	RCI = -41.36 + 5.76 DWT	0.987	0.01
2	RCI = 6.47 + 4.33 DWT	0.980	0.01
3	RCI = 38.90 + 2.62 DWT	0.984	0.01
4	RCI = 43.08 + 1.60 DWT	0.960	0.01
5	RCI = 36.20 + 1.66 DWT	0.898	0.01
6	RCI = 27.36 + 1.87 DWT	0.847	0.02

It is evident from Figure 19 that the slope of the regression lines generally decreases from the first sample area to the sixth sample area, while the intercept of the regression lines increases from the first sample area to the sixth sample area. The change in the slope and intercept of the regression lines was related to the change in the clay content of the soil. A high correlation was found to exist between the slope and intercept of the regression lines and the clay content. The correlation coefficient between the slope and the clay content was -0.984 which is significant at 0.01 level. The negative sign means that the slope decreases as the clay content increases. The correlation coefficient between the intercept and the clay content was 0.907 which is significant at 0.02 level. The regression equations relating the slope to clay content and the intercept to clay content are, respectively:

$$S = 16.71 - 0.40\ C \tag{3}$$

and

$$I = -219.43 + 6.93\ C \tag{4}$$

where

S = slope of regression line of rating cone index versus depth to water table

C = % clay content

I = intercept of regression line of rating cone index versus depth to water table

The resulting equation relating rating cone index (RCI) to depth to water table (DWT) and clay content (C) can then be written as follows:

$$RCI = -219.43 + 6.93\ C + (16.71 - 0.40\ C)DWT \tag{5}$$

If the depth to water table and clay content of a soil are known, the strength of the soil, expressed by the rating cone index, can, therefore, be determined using Equation 5.

Relations Between Soil Strength and Moisture Content

Previous studies (1, 16) have indicated that for most soils, the strength-moisture content relation could be described by a logarithmic equation. It was assumed that a logarithmic relation would apply to the soils of this study. The strength-moisture content relations are expressed by the equation

$$Y = A\ (MC)^{B} \tag{6}$$

where

Y = strength parameter (cone index, remolding index, or rating cone index)

MC = moisture content

A and B = equation constants

This expression may be reduced to log form:

$$\log Y = \log A + B \log MC \tag{7}$$

or

$$\log Y = D + B \log MC \tag{8}$$

in which

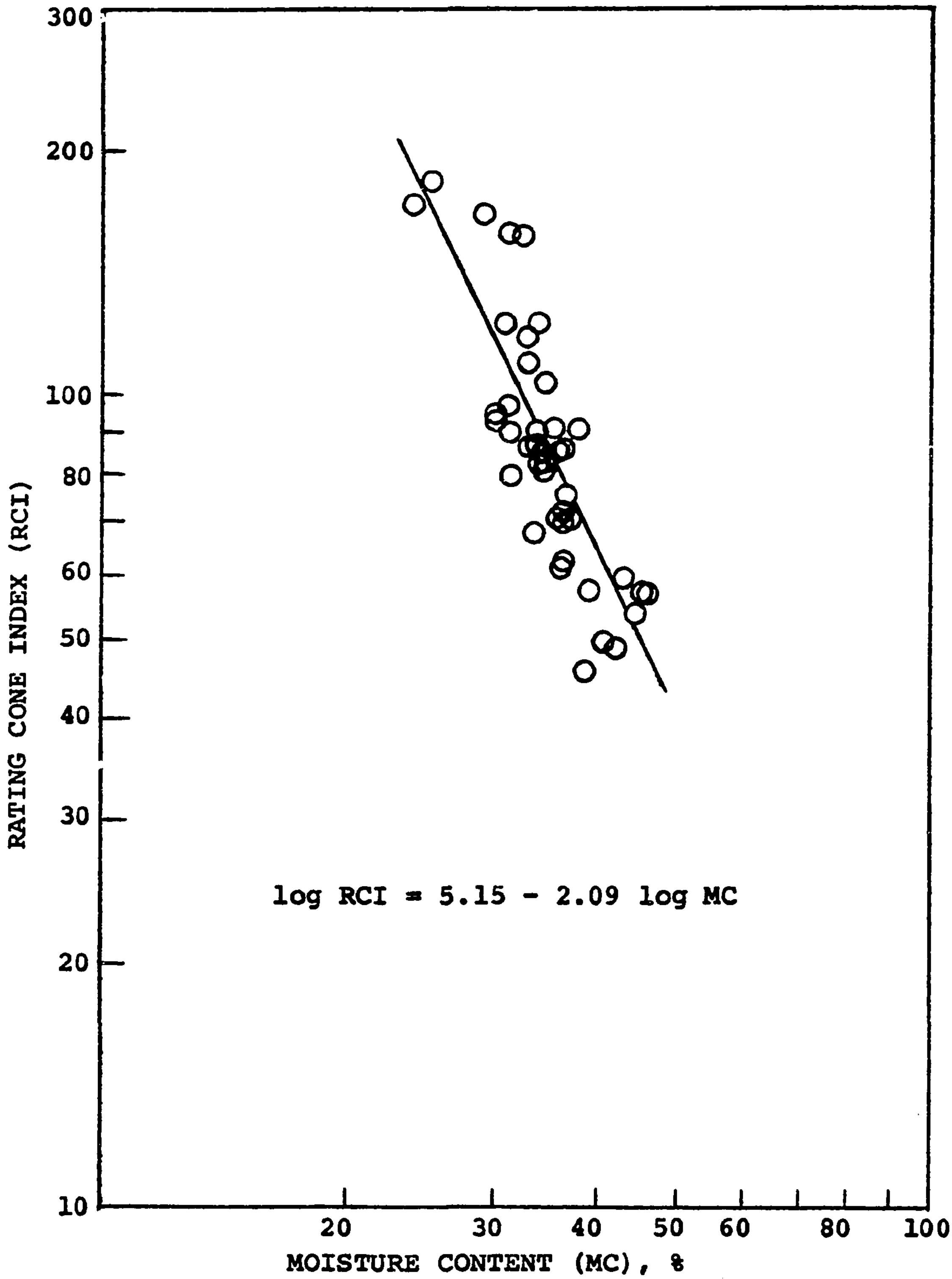
$$D = \log A$$

Values of rating cone index and moisture content that were obtained at the Swine Breeding Farm were tabulated in Table 4. These values were plotted as shown in Figure 20, and a regression line was obtained using the method of least squares. The regression equation of the line is:

$$\log RCI = 5.15 - 2.09 \log MC \tag{9}$$

The correlation coefficient between rating cone index and moisture content was -0.827 which is significant at 0.01 level. From Figure 20, the rating cone index values that

Figure 20. Rating cone index versus moisture content for Swine Breeding Farm


300
200
100
80
60
50
40
30
20
10
20
30
40
50
60
80
100
RATING CONE INDEX (RCI)
MOISTURE CONTENT (MC), %
log RCI = 5.15 - 2.09 log MC

correspond to the liquid limit (45% moisture content) and plastic limit (33% moisture content) are 49 and 93 respectively.

Values of rating cone index and moisture content that were obtained from laboratory tests conducted on soil obtained from the sixth sample area of the Swine Breeding Farm were tabulated in Table 5. Figure 21 shows rating cone index plotted versus moisture content for the soil contained in two barrels used in the laboratory tests. The regression equations of the lines for barrels 1 and 2 are, respectively:

$$\log RCI = 5.50 - 2.33 \log MC \tag{10}$$

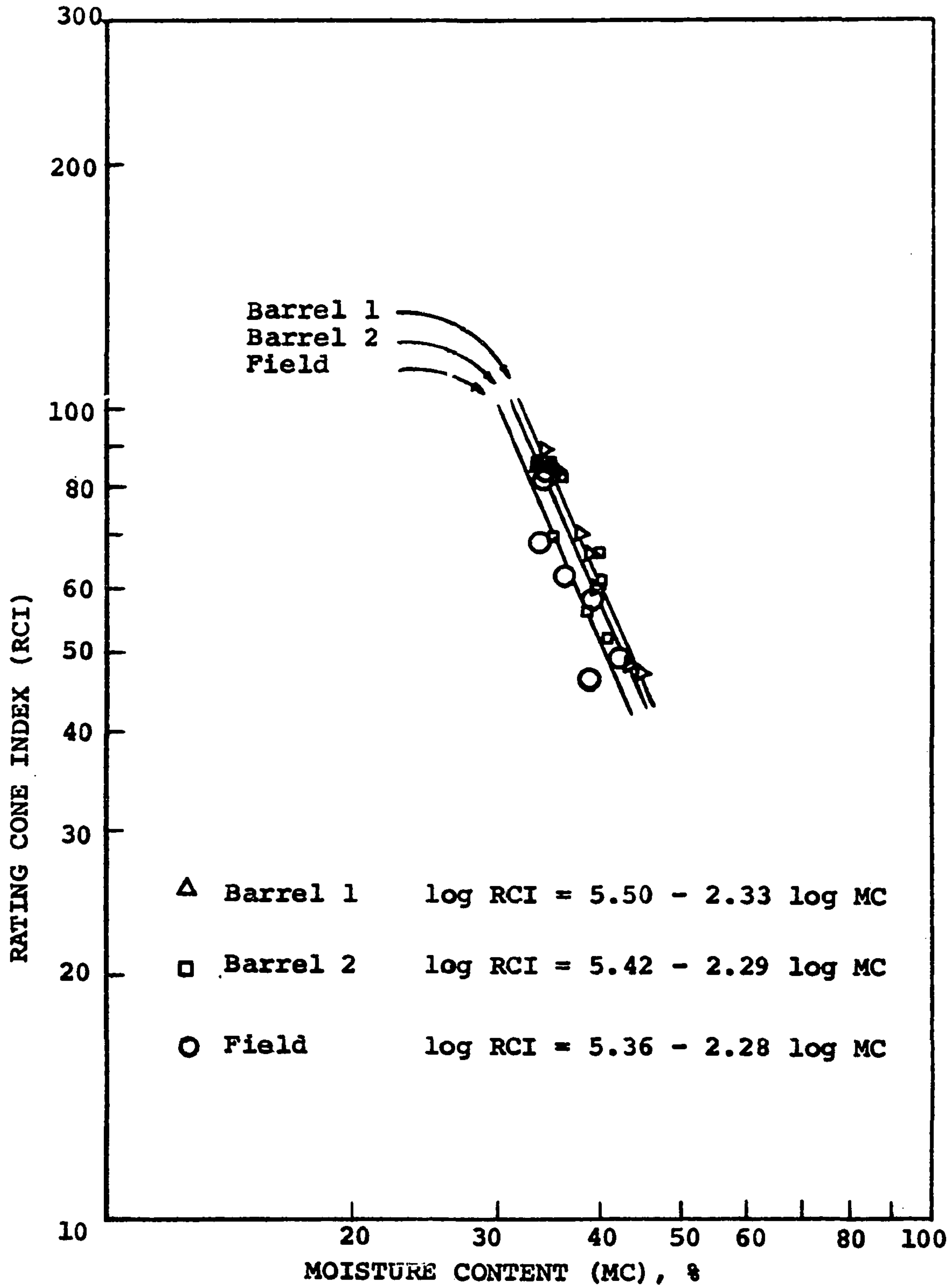
and

$$\log RCI = 5.42 - 2.29 \log MC \tag{11}$$

The correlation coefficient between rating cone index and moisture content for barrel 1 was -0.983 which is significant at 0.01 level. The correlation coefficient for barrel 2 was -0.881 which is also significant at 0.01 level. The negative sign in the correlation coefficients means that the rating cone index decreases with increasing moisture content.

In order to compare these relations with those obtained from data collected in the field, values of rating cone index and moisture content obtained from the sixth sample area of the Swine Breeding Farm were also plotted in

Figure 21. Rating cone index versus moisture content from laboratory and field tests



300
200
100
80
60
50
40
30
20
10
RATING CONE INDEX (RCI)
20
30
40
50
60
80
100
MOISTURE CONTENT (MC), %
Barrel 1
Barrel 2
Field
Barrel 1 log RCI = 5.50 - 2.33 log MC
Barrel 2 log RCI = 5.42 - 2.29 log MC
Field log RCI = 5.36 - 2.28 log MC

Figure 21. A regression line was obtained by the method of least squares. The equation of this line is:

$$\log RCI = 5.36 - 2.28 \log MC \qquad (12)$$

The correlation coefficient between rating cone index and moisture content for the sixth sample area was -0.842 which is significant at 0.02 level. Figure 21 and Equations 10, 11 and 12 show that the relations between rating cone index and moisture content obtained from the laboratory tests agree with that obtained from the field. From Figure 21, the average laboratory values of rating cone index that correspond to the liquid limit and plastic limit of the soil are 44 and 89 respectively.

The degree of saturation, which is the actual amount of moisture in the soil expressed as a percentage of the maximum amount which the soil would contain if saturated, is indicative of pore water pressure. Values of degree of saturation were calculated from values of moisture content and bulk density, obtained from Swine Breeding Farm, and assumed specific gravity of 2.7. These are shown in Table 4. Rating cone index (RCI) was correlated to degree of saturation, S'; the regression equation was:

$$\log RCI = 4.53 - 1.39 \log S' \qquad (13$$

The correlation coefficient between rating cone index and degree of saturation was -0.445. It is significant at 0.01

level, but lower than that obtained between rating cone index and moisture content. This implies that pore pressure is less important than moisture content in fine-grained soils.

EFFECT OF TILE DRAINAGE ON WATER TABLE LEVEL

Previously, relationships were developed between rating cone index, which is considered as a measure of soil trafficability, and depth to water table. In order to determine the effect of tile drainage on trafficability, it is essential therefore to study the effect of tile drains on water table level.

Schwab et al. (35) studied the effect of tile spacing on crop yield and water table level in a Planosol soil (claypan soils of flat lands). Spacings of 15, 30, and 60 ft. were used. They reported that the water table midway between the 15-ft. spacings was as much as 0.5 ft. lower than that midway between the 60-ft. spacings. It was also found that for all the spacings the water table was nearly flat and at 5 ft. from the tile was seldom more than 0.3 ft. lower than midway between the tile.

Vaigneur (50) and Vaigneur and Johnson (51) used precipitation records from 1933-1962 to predict water table fluctuations for designated soil characteristics and predetermined drainage facilities. The expected frequency of a given degree of drainage protection was investigated for central Iowa rainfall patterns under continuous corn cropping.

Since some of the results obtained by Vaigneur and Johnson will be used in this study, it is essential to briefly describe how they arrived at those results. The portion of precipitation that contributed to drainage needs (excess moisture) was first determined by the use of a water balance. The accumulation of excess moisture was then related to the behavior of the water table for various tile spacings, soil conductivities, and locations of the impervious layer. The main assumptions that were made in the study are:

1. All tile installations were made at a depth of 4 ft.
2. An impervious layer below the tile prohibited deep percolation
3. The primary demand for drainage could be limited to the period of April, May, and June
4. When the water table exceeded the limit from the tile line to the soil surface, the remaining excess was removed as additional runoff.

The last assumption implies that when the excess for a given day caused the water table to rise above the ground surface, the excess necessary to bring the water table to the soil surface was subtracted from the total excess for that day and the remaining portion of the excess was considered as additional runoff.

A transient-flow equation was used by Vaigneur and Johnson to calculate daily water tables for hydraulic conductivities, K, of 1, 2, 4 and 8 ft./day, tile spacings, S, of 40, 80, 160 and 320 ft., and a depth to the impervious layer, h, of 4 ft. below the tile. Recurrence intervals for specified water tables and durations were developed from tabulations of the calculated daily water tables. Recurrence intervals of 10, 5, 2, 1, 1/2 and 1/3 years were used where feasible. The recurrence intervals were based on water table data from April, May, and June for the years 1933 through 1962.

Figures 22 and 23 show the frequency of minimum water table heights for minimum durations when K = 1 ft./day and K = 2 ft./day respectively (50). The smooth curves were drawn visually to the best fit of the points on the graphs. By placing all graphs for common K-values and h-values within the same figure, it is convenient to compare the effect of tile spacing upon the expected recurrence of a given drainage requirement. These graphs will be used later in the application of results.

Figure 22. Frequency of minimum water table heights for minimum durations when $K = 1$ ft./day, and $h = 4$ ft., Ames, Iowa (50)

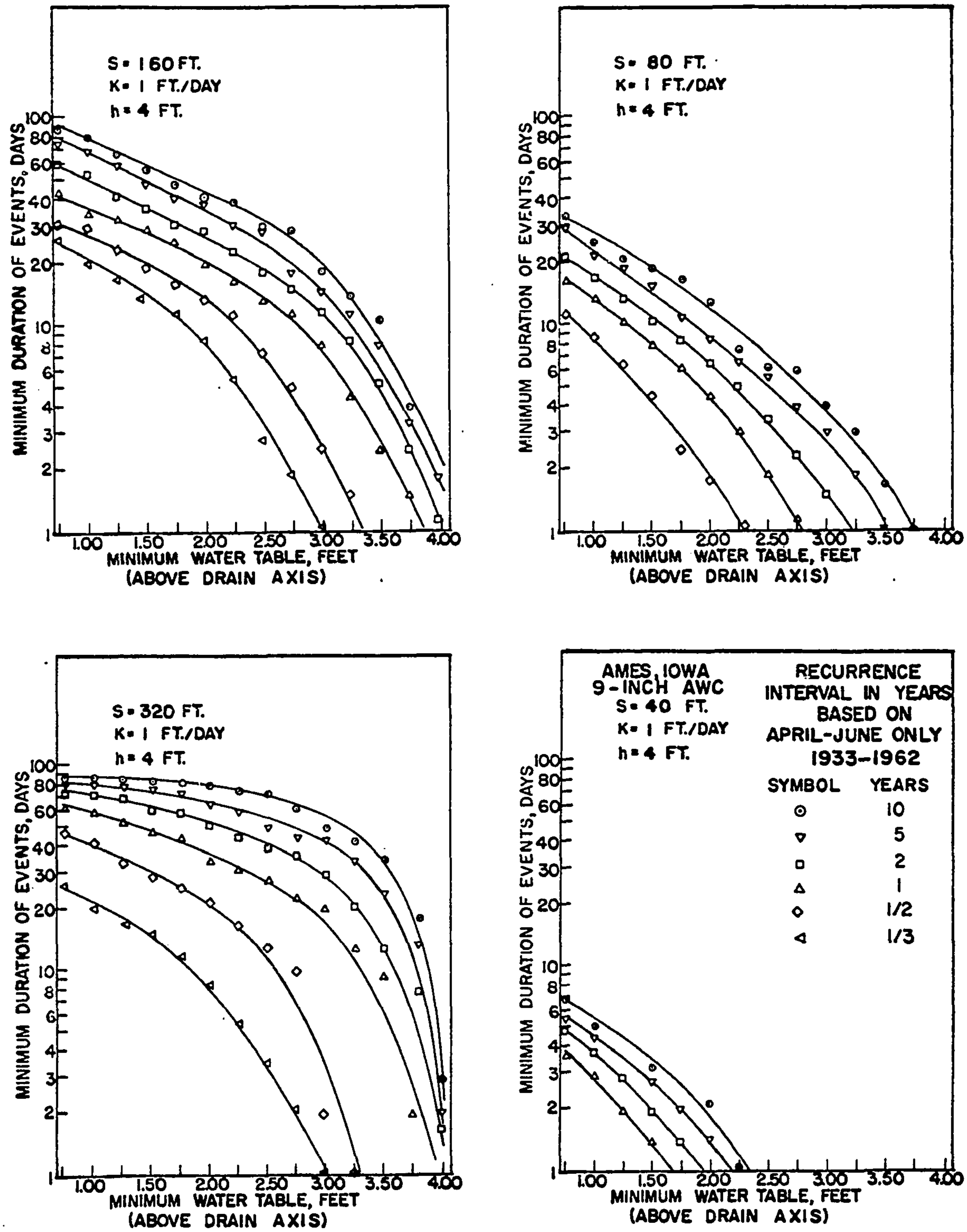
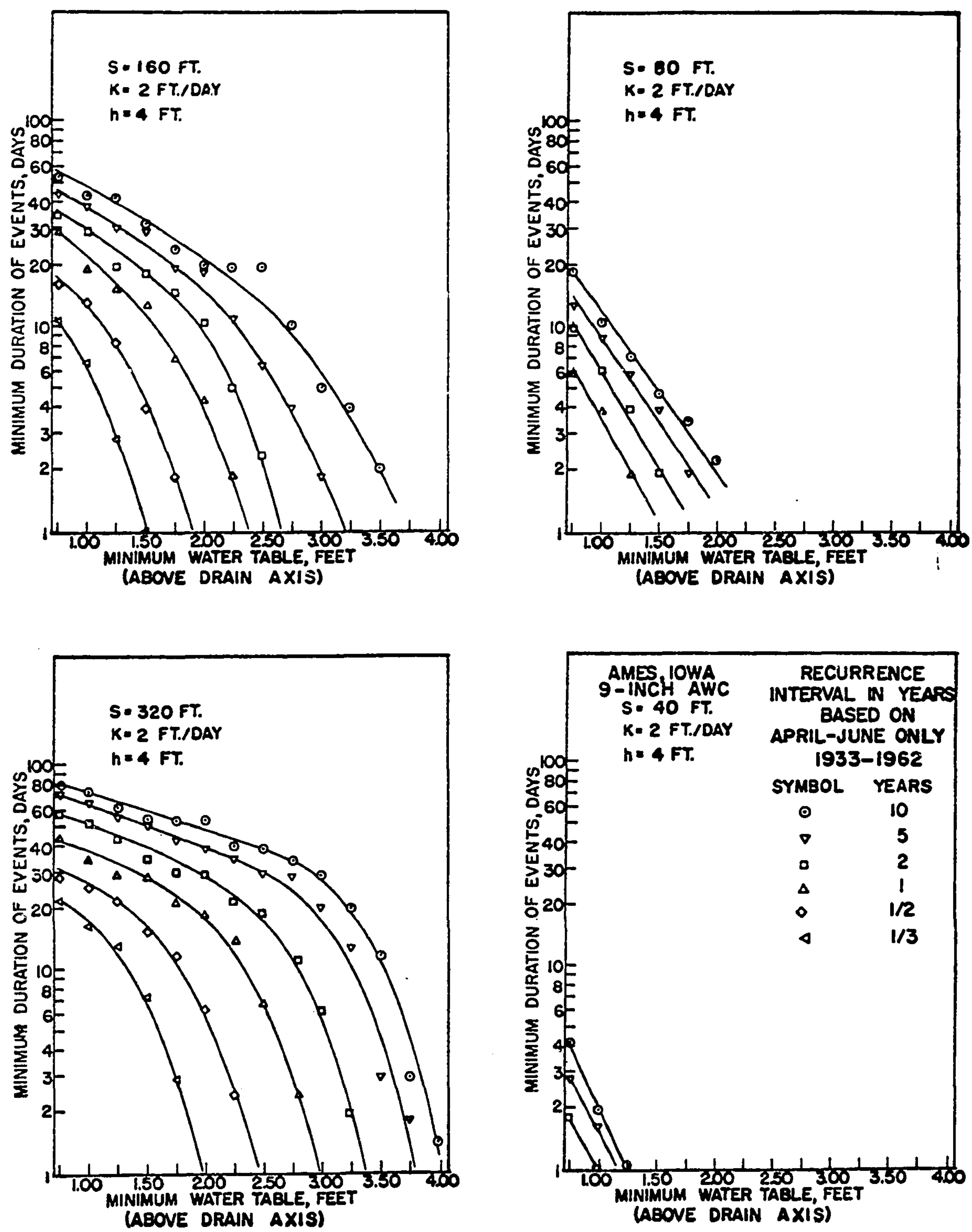

S= 160 FT.
K= 1 FT./DAY
h= 4 FT.
MINIMUM DURATION OF EVENTS, DAYS
MINIMUM WATER TABLE, FEET
(ABOVE DRAIN AXIS)
S= 80 FT.
K= 1 FT./DAY
h= 4 FT.
MINIMUM DURATION OF EVENTS, DAYS
MINIMUM WATER TABLE, FEET
(ABOVE DRAIN AXIS)
S= 320 FT.
K= 1 FT./DAY
h= 4 FT.
MINIMUM DURATION OF EVENTS, DAYS
MINIMUM WATER TABLE, FEET
(ABOVE DRAIN AXIS)
AMES, IOWA
9-INCH AWC
S= 40 FT.
K= 1 FT./DAY
h= 4 FT.
RECURRENCE INTERVAL IN YEARS BASED ON APRIL-JUNE ONLY 1933-1962
SYMBOL YEARS
10
5
2
1
1/2
1/3
MINIMUM DURATION OF EVENTS, DAYS
MINIMUM WATER TABLE, FEET
(ABOVE DRAIN AXIS)

Figure 23. Frequency of minimum water table heights for minimum durations when K = 2 ft./day, and h = 4 ft., Ames, Iowa (50)


S= 160 FT.
K= 2 FT./DAY
h= 4 FT.
S= 80 FT.
K= 2 FT./DAY
h= 4 FT.
S= 320 FT.
K= 2 FT./DAY
h= 4 FT.
AMES, IOWA
9-INCH AWC
S= 40 FT.
K= 2 FT./DAY
h= 4 FT.
RECURRENCE INTERVAL IN YEARS BASED ON APRIL-JUNE ONLY 1933-1962
SYMBOL YEARS
10
5
2
1
1/2
1/3
MINIMUM DURATION OF EVENTS, DAYS
MINIMUM WATER TABLE, FEET
(ABOVE DRAIN AXIS)
1.00
1.50
2.00
2.50
3.00
3.50
4.00
1
2
3
4
6
8
10
20
30
40
60
80
100

ECONOMIC ASPECTS OF TILE DRAINAGE

Farmers, agronomists, and agricultural engineers are becoming increasingly concerned with the cost of damage caused by excess water and untimely field operations. van Schilfgaarde made the following statement when he closed his discussion of drainage research (52, p. 9):

> An important aspect of drainage research today is the question of measuring the benefits derived from a drainage system. One important component concerns the evaluation of the effect of drainage on the timeliness of farm operations. The water status of the soil must be such that not only plant roots can perform their function properly to obtain good growth, but that the farmer can enter the field at the proper time to perform operations such as plowing, cultivation, spraying, or harvesting. "Proper" here means appropriate to the need of the crop as well as appropriate to the work schedule of the farmer. Furthermore, the farmer needs to enter not just most of his field at this time, but all of it, as small wet spots could greatly hamper his efficiency. We need to answer the question: How do we quantify the effect of "timeliness" and relate it to the cost of alternative drainage systems?

It is worthwhile to look at the effect of excess water on crop yield and then discuss the effect of tile drainage on the timeliness of farm operations.

The amount of damage caused by excess water depends upon the plant species, the length of inundation or water-logged conditions, and the stage of plant growth, among other things. Ritter and Beer (30) observed corn yields were affected most by flooding at the early stages of growth.

Once the corn reached the silking stage, shallow depths of flooding did not cause noticeable amounts of damage. They reported that under some natural flooding conditions, corn plants in the early stages of growth will be completely killed by inundation periods of 4 to 5 days. DeBoer and Ritter (11) studied corn and soybean damage during periods of excess rainfall on areas with shallow depressions. They reported one observation where the corn was approximately 12 in. high at the time of flooding, and the soybeans were flooded approximately 20 days after emergence. The corn yields were reduced after 2 1/2 days of flooding, and all corn plants were killed after 3 1/2 to 4 days of inundation. The soybean plants were killed after 3 days of flooding. After another storm the corn was approximately 20 to 24 in. high at the time of flooding, and the soybeans were flooded 30 to 35 days after emergence. The corn yields were significantly reduced for flooding periods greater than 4 days, and all corn plants were killed after 6 to 7 days of inundation. The soybean yields were reduced after 3 to 4 days of inundation, and the soybean plants were killed after 3 1/2 to 5 days of flooding.

Tile drainage is one of the most widely used practices for reducing excess water in poorly drained soils. Several experiments have been conducted to determine the drainage need of crops and the economic return from drainage. Beer and Johnson (3) have written a fifteen-year summary of corn yields from tile drainage experiment in Edina soils of Iowa. Schwab _et al_. (35) studied the effect of tile spacing on crop yield in a Planosol soil (claypan soils of flat lands). Tile spacings of 15, 30 and 60 ft. were used. They found that corn and oat yields on the 15- and 30-ft. spacings varied from 3.4 to 9.1 bushels per acre higher than the yields on the 60-ft. spacings. Beer _et al_. (4) conducted tile spacing experiments on the Southern Iowa Experimental Farm. They reported that, for rotation corn, yields for the 15-ft. tile spacing have, on the average, been 6 bushels per acre higher than for the 60-ft. spacing. For continuous corn, the average increase has been 4 bushels per acre for the 15-ft. spacing over the 60-ft. spacing. A comparison was made between the yields on the 60-ft. tile spacing and plots where no tile had been installed. It was found that the average advantage for the tiled plots was 13 bushels per acre on rotation corn and an estimated 1 bushel per acre advantage on tiled plots for continuous corn. It was also found that legume yields have averaged about 0.4 ton per acre greater on the tiled plots than on the plots without tile. It was concluded that it is probable that the tiled rotation plots had a more adequate nitrogen supply than did the plots without tile. Therefore, the difference in corn yield was, at least in part, due to a fertility difference which was indirectly an effect of drainage.

In the experiments mentioned above, tillage, planting, and harvesting operations were conducted on all treatments at the same time. Thus, no credit was given to the drained plots for potential earlier planting and crop salvage in case of extremely wet harvesting conditions.

Circumstances may arise whereby any farmer will lose all or part of his crops because timely field work is impossible. It is a matter of chance that planting, cultivation or harvesting of a crop may be delayed until the crop suffers. Generally, the possibility of untimely operation of machines is held to be a factor which either increases annual cost of the machines or decreases the income obtained from use of the machine. According to Buchele et al. (10), the cost of a 1 hour delay of various farm operations can be calculated from the equation

$$c = K'AYV \tag{14}$$

where

c = Hourly cost of loss

K' = Timeliness factor (1/hour)

A = Area (acres)

Y = Potential yield, if no losses occur (bushels/acre)

V = Value (dollars/bushel)

Table 12. Values of K' for various crops and operations (10)

Operation	K'
Planting corn and soybeans	0.00100
Seeding	0.00030
Tillage	0.00005
Cultivation	0.00020
Grain harvesting	0.00030
Soybean harvesting	0.00070
Hay harvesting	0.00050
Green forage harvesting	0.00010

The timeliness factor, K', is the decimal reduction in crop yield due to a 1 hour delay in performing an operation. Table 12 shows the values of K' for a number of crops and operations. The total cost of the delay in entering the field after the crop is ready for harvest is given by

$$c_a = c\ N_a \tag{15}$$

where

c_a = Total cost of delay of entry

N_a = Total working hours entry is delayed

Planting and harvesting are probably the most critical operations for many crops. Major losses occur when planting and harvesting are delayed to the point that inclement weather forces abandonment of the crop. Some farmers want machinery with as much capacity as money can buy to get the planting and harvesting done on time. Since planting is a more critical operation than harvesting for most crops, the following discussion will be concentrated on the economic aspects of untimely planting.

The economic penalty associated with untimely planting has been studied recently by several investigators. Figure 24 shows 4-year averages for four varieties of corn grown in central Iowa reported by Frisby and Bockhop (14). The optimum planting date for the full-season varieties was April 24. The sacrifice in yield for delay in planting was approximately 1 bushel per day. Marley and Ayres (24) conducted an experiment at Ames, Iowa, during 1967 and 1968 to measure corn planting timeliness. Table 13 gives a summary of the yield data for 1967 and 1968. The yield reduction for the second planting date of 1967 was due to the low plant population for that date. The plant population reduction was caused by an infestation of wireworms, and was noted in all plots for the second planting date. The other planting dates were not affected. Figure 25 shows planting timeliness function, presented by Link (22), for corn.

Figure 24. Date of planting versus yield, summary of four years data on four different varieties (14)

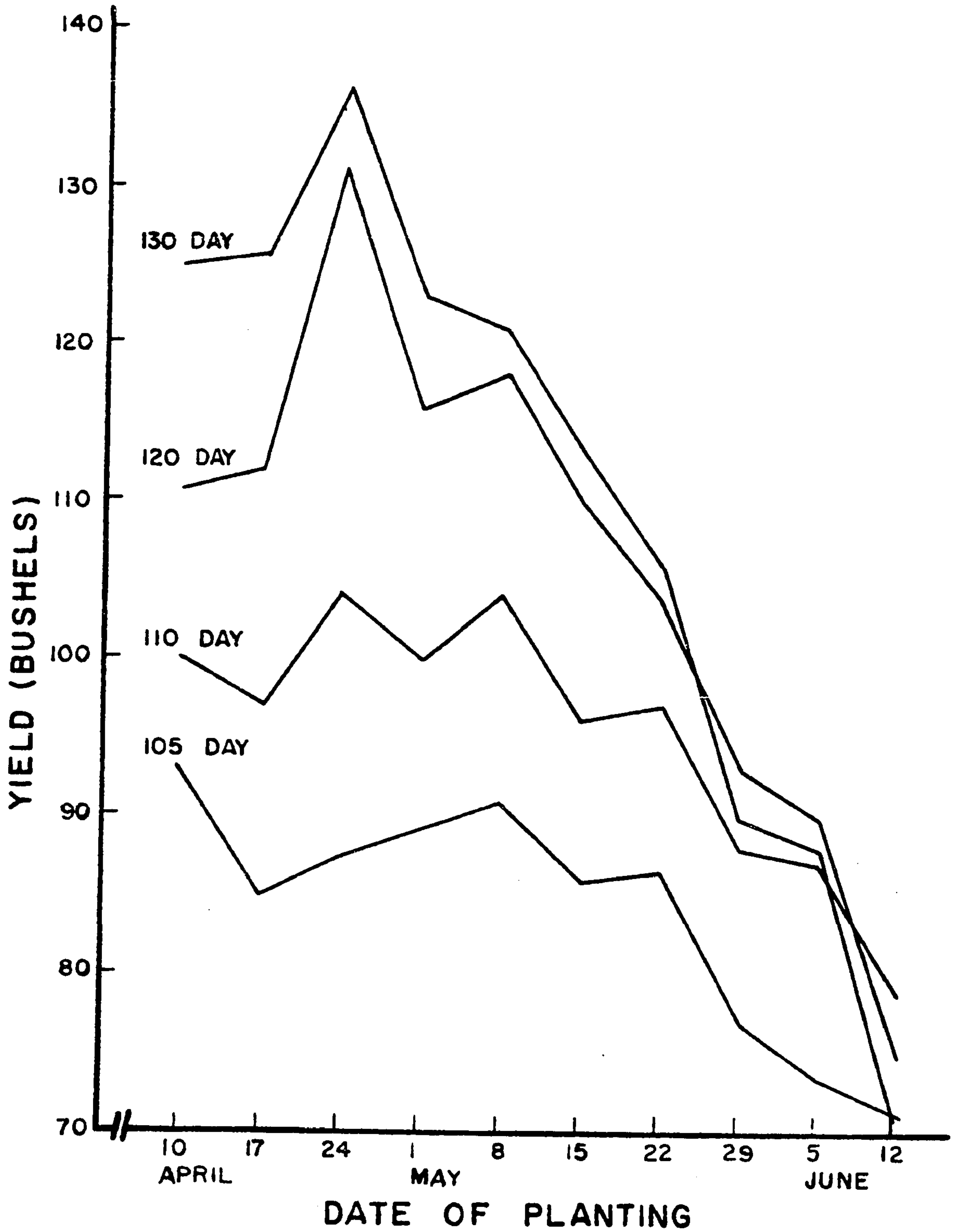
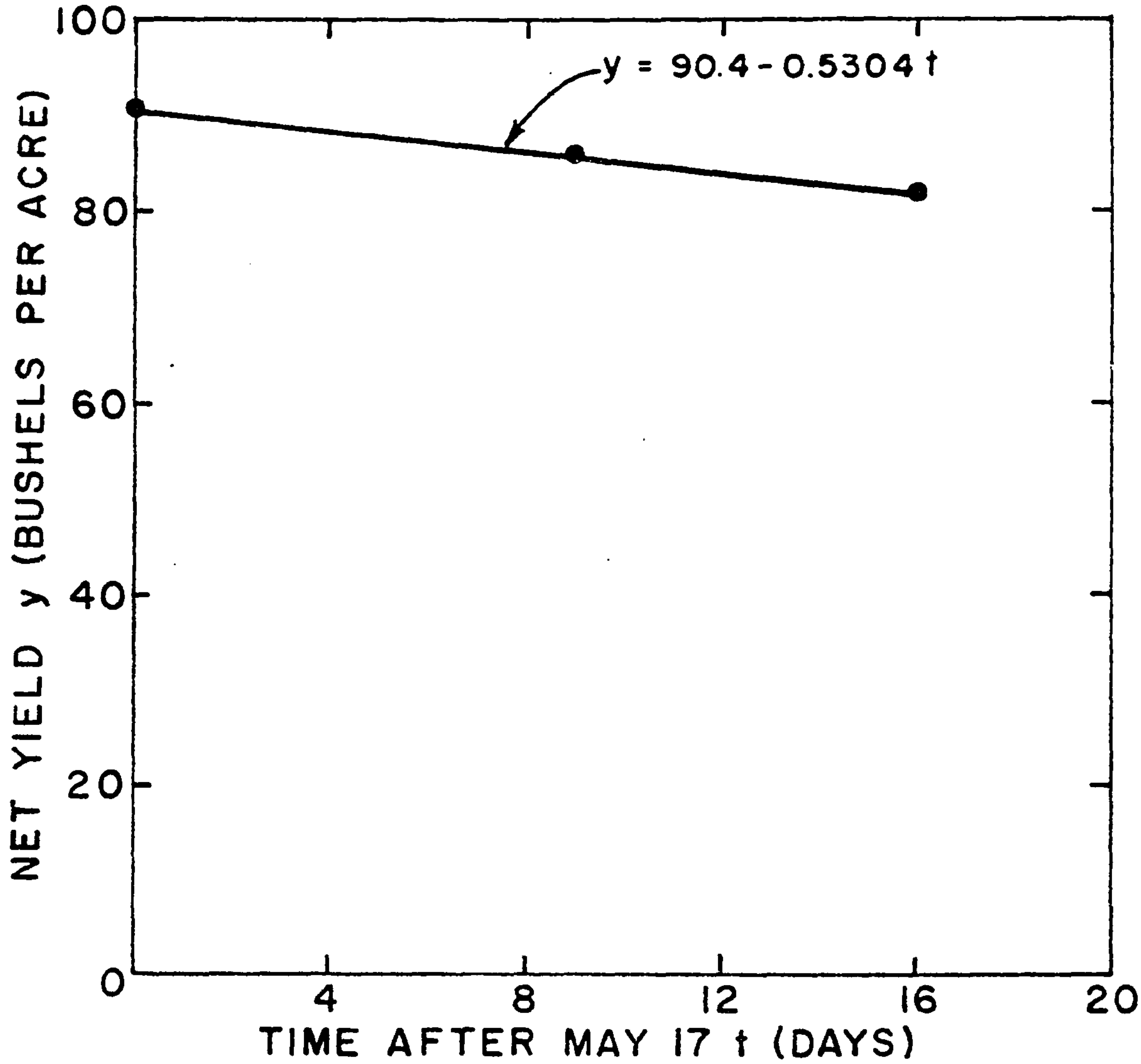

140
130
120
110
100
90
80
70
130 DAY
120 DAY
110 DAY
105 DAY
YIELD (BUSHELS)
10
17
24
1
8
15
22
29
5
12
APRIL
MAY
JUNE
DATE OF PLANTING

Table 13. Yield and average plant population for six planting dates (24)

Planting date	Variety 1	Variety 2	Variety 3	Average plant population
	1967 Yield, bushels/acre			
April 24	134.2	139.1	131.0	16640
April 29	120.8	129.3	117.3	12490
May 4	130.4	139.1	121.7	16690
May 9	130.8	134.2	111.1	16630
May 14	123.7	128.4	111.8	16170
May 19	117.5	114.6	89.3	16320
Mean	126.2	130.8	113.7	
	1968 Yield, bushels/acre			
April 24	117.0	136.9	129.9	22930
April 29	112.1	145.1	140.7	20180
May 4	119.1	132.4	128.6	20460
May 9	116.4	141.2	135.4	20640
May 14	118.9	131.8	127.6	20890
May 19	116.1	127.1	116.8	19960
Mean	116.6	135.7	129.8	

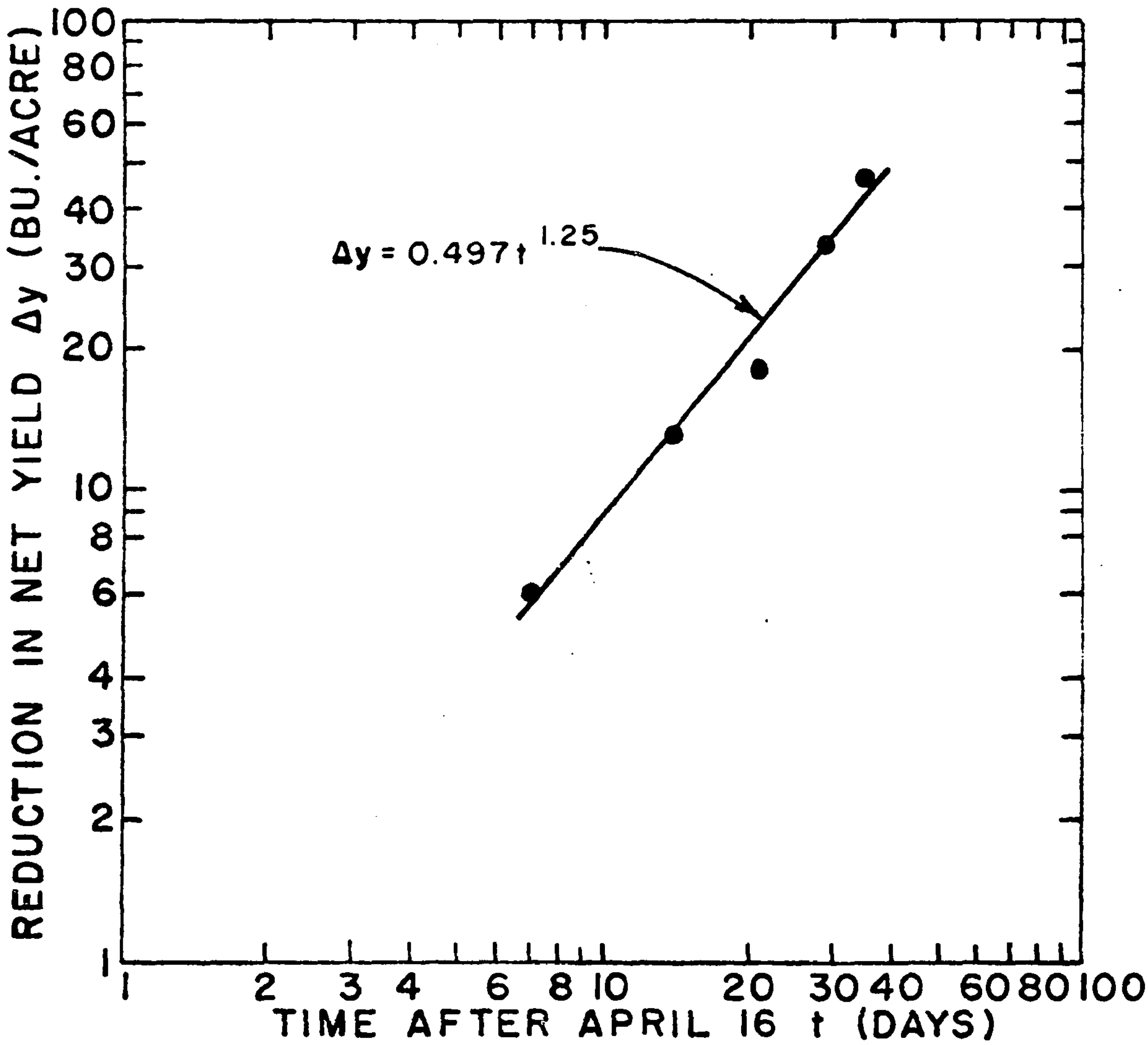
The data were six year averages for 10 double cross corn hybrids, varying from those suited to northern Iowa to those suited to southern Iowa. The reduction in net yield due to planting delay for oats is given in Figure 26. It was

Figure 25. Corn planting timeliness function (22)



y = 90.4 - 0.5304 t
NET YIELD y (BUSHELS PER ACRE)
100
80
60
40
20
0
4
8
12
16
20
TIME AFTER MAY 17 t (DAYS)

Figure 26. Reduction in yield versus planting delay for oats



REDUCTION IN NET YIELD Δy (BU./ACRE)
100
80
60
40
30
20
10
8
6
4
3
2
1
1
2
3
4
6
8
10
20
30
40
60
80
100
TIME AFTER APRIL 16 t (DAYS)
Δy = 0.497t 1.25

based on experiments, reported by Link (22), conducted in Ames, Iowa. According to Buchele (10), the sacrifice in yield for delay in planting soybeans is 1/3 bushel per day.

Therefore, experiments relating planting date to crop yield usually show a favorable yield response to early planting. Early planting, in most cases, increases the yield without increasing the producer's cost per acre. Since tile drains are designed to reduce excess moisture in poorly drained soils, these drains will increase the number of days on which machine operations can be made during the planting season and, therefore, increase the probability of early planting.

DISCUSSION AND APPLICATION OF RESULTS

The main objectives of this study were (a) to determine the effect of tile drainage on trafficability of soil and mobility of agricultural equipment and (b) to estimate the added economic benefit of tile drainage due to timely crop planting.

In order to achieve these objectives, the performance of a vehicle was first related to soil strength in terms of rating cone index. The rating cone index was determined by the cone penetrometer and remolding apparatus. The cone penetrometer did an excellent job in giving an indication of the in-place soil shearing strength. It has the advantage that many measurements can be made rapidly at the surface and at some depths below the surface. It is easy to carry to the field and is not difficult to use.

Variations in the configuration of the cone penetrometer and the manner in which the penetration test is run can cause large variations in the results. Some of the features that could influence the test data are: size of penetrometer shaft relative to the cone size, the surface finish of the cone, and rate of penetration (12, 29). In this study, the standard trafficability cone penetrometer, developed by the Waterways Experiment Station, was used. It has a 30-degree cone with 1/2 sq. in. base area.

The shear strength of soil is considered to be composed of two components, cohesion and friction, with the function relation expressed by the Coulomb equation, $\tau = c + p \tan \emptyset$. If the cone penetrometer test is examined on these terms, it is apparent that the cone index does not differentiate between cohesion and friction. In many practical cases, however, either the parameters can be determined or estimated by some other means, or separation of the two parameters is not necessary. Trafficability and mobility studies carried on at the Waterways Experiment Station, reported by Freitag (12) showed that whenever a strength measurement is needed in a wet, fine-grained soil whose friction angle can be considered zero, the cone penetrometer can provide the needed information with considerable accuracy. Where separation of cohesion and friction is not necessary, the penetrometer can be useful directly. Therefore, when used in a knowledgeable way, the cone penetrometer is an extremely useful device.

Relations were developed between soil strength (in terms of rating cone index), moisture content, and depth to water table for poorly drained soils from field measurements and laboratory tests. It is evident from the analysis of data that there was a high correlation between rating cone index at the critical layer (6- to 12-in. depth) and depth to water table. The correlation coefficients between rating cone index and depth to water table were significant at 0.01 level for all sample areas of the Swine Breeding Farm except that for the sixth sample area which was significant at only 0.02 level. The significant correlation between rating cone index and depth to water table is due to the fact that as the depth to water table increases the moisture content of soil in the critical layer decreases and, therefore, the strength of soil in the critical layer increases. For fine-grained soils and sands with fines, the rating cone index decreases with increasing moisture content. This is supported by Figure 20 in which rating cone index was plotted versus moisture content.

From the analysis of data, it was shown that the correlation between the slope of the regression line of rating cone index versus depth to water table and the clay content was significant. The slope was found to decrease as the clay content increases. This may be due to the effect of the capillary forces, or the rise of water in the capillary pores. As the clay content increases the capillary forces increase and, therefore, the influence of water-table level on moisture content at the critical layer decreases.

Results have shown that relationships between rating cone index and moisture content obtained from the laboratory tests agree with that obtained from the field. Therefore, results from laboratory tests, which could be more convenient to obtain, especially under adverse weather conditions, may replace those obtained from the field. However, since the laboratory tests were conducted on soil samples obtained from one sample area, it is difficult to justify the validity of the results for other soils.

Rut depth measured after the passage of a vehicle is indicative of soil strength. Rut depth normally decreases as soil strength increases. This was supported by the tractor tests in which rut depth was measured (from the ground surface) after the second pass at 10-ft. stations along each path. Tables 6, 7, and 8 show that the average rut depths were lower in the first test lane than those in the third test lane, while the average cone index values were higher in the first test lane than those in the third test lane. Values of moisture content and rating cone index obtained from the tractor tests, given in Table 9, show, again, that the rating cone index decreases with increasing moisture content.

The effect of tile drainage on water-table level can be determined from Figures 22 and 23, which were developed by Vaigneur (50). In the development of these graphs, the critical period for drainage needs was limited to the months of April, May, and June. This was influenced by the use of central Iowa as a control location. In this region, the frost leaves the ground late in March or early in April and is followed by wet conditions due to snow melting and spring rains. The average rainfall during this period is 11.38 in., and the use of water by plants is very limited. The last of June was selected as the end of the critical period on the basis of water-table level and the extent of the development of a crop in central Iowa. This assumption was supported by water table measurements in a Webster Silt Loam soil. Figures 22 and 23 can be used to determine the minimum duration of a minimum water-table level at some specified recurrence interval. For example, with a tile spacing, S = 160 ft. and a hydraulic conductivity, K = 1 ft./day, Figure 22 shows that the minimum duration of a minimum water table height of 2.5 ft. above the drain is approximately 15 days at a recurrence interval of one year. It should be remembered that all tile installations were made at a depth of 4 ft., and a height of 2.5 ft. above the drain is equivalent to a depth of 1.5 ft. below the ground surface. As tile spacing decreases, the water-table duration, at some specified recurrence interval, decreases.

The economic cost associated with untimely planting was discussed previously with the economic aspects of tile drainage. It is clear that crop yields are reduced considerably when planting is delayed due to untimely farm operations caused by excess soil moisture. The results of this study can be applied to determine the increased number of days in which machine operations can be performed during the planting season when tile drains are installed with various spacings. An estimate can then be made of the added economic benefit of tile drainage resulting from increased mobility of agricultural equipment and timely crop planting.

Since all the results are applicable to central Iowa, typical central Iowa crops and field operation schedules will be assumed. Corn and soybean are normally grown in central Iowa. In fact many farmers prefer growing corn if they can plant it early. The critical period for corn planting in central Iowa is normally April 20 to May 20, while that for soybean is May 10 to June 1. Planting before or after the critical period will result in reduction in crop yield. Delay in planting is normally caused by untimely farm operations due to excess moisture. The period of one and a half months between April 15 and June 1 is usually considered the critical period for farm operations.

Plowing is one of the most critical and difficult field operations that are normally performed during the planting season (assuming spring plowing). It is necessary, therefore, to determine the soil strength (in terms of rating cone index) required for this operation. This can be done by means of Appendix B and Figure 2. For example, the soil strength required to support an Oliver 1855, Diesel tractor pulling a six-bottom plow, which is currently used by many farmers, can be determined by first evaluating the force necessary to pull the plow. According to Marley (23, p. 83), the draft for a plow is 630 pounds per foot width. This will result in a required force to pull the plow equal to

$$(6)(630)(\frac{16}{12}) = 5040 \text{ pounds (assuming 16-in. bottoms).}$$

The pull expressed in percent of the tractor weight will be

$$(\frac{5040}{13,000})\ 100\% = 39\%$$

Then, using Figure 2, the required rating cone index will be +30 above vehicle cone index. Since the vehicle cone index for the tractor is 43 (from Appendix B), the total rating cone index required for the plowing operation will be

$$43 + 30 = 73$$

From Figure 19 (or Equation 5), it was found that a depth to the water table of 1 1/2 to 2 ft. is required to give a rating cone index of 73 for the soils used in this study. Therefore, a depth to the water table of 2 ft. is considered adequate for the plowing operation using the example machine.

Although it was found from the trafficability standpoint that, when the water table is 2 ft. below the ground surface, plowing can be performed, many farmers do not plow in this condition in order to avoid compacting the soil. On the other hand, many farm operations could be performed during the planting season when plowing is almost impossible. To simplify the problem, however, it will be assumed that the field will be workable when the water table is at least 2 ft. below the ground surface.

Now, assume a hydraulic conductivity, K = 1 ft./day and a tile spacing, S = 320 ft. From Figure 22, the minimum duration of a minimum water table height of 2 ft. above the drain is approximately 37 days at a recurrence interval of one year. A water table height of 2 ft. above the drain is equivalent to a depth of 2 ft. below the ground surface. Therefore, with a recurrence interval of one year, the field will not be workable for 37 days when the spacing, S, is 320 ft. If the spacing is decreased to 160 ft., the field will not be workable for approximately 21 days. Furthermore, with a spacing of 80 ft., the field will not be workable for only 5 days. Therefore, the number of non-workable days decreases as the tile spacing decreases.

The 80-ft. spacing is widely used in central Iowa among those given in Figure 22. The 320-ft. spacing is the widest spacing given in Figure 22. With a recurrence interval of one year, the non-workable days for 80-ft. and 320-ft. spacings are 5 and 37 days respectively. Therefore, 32 working days are gained by decreasing the spacing from 320 ft. to 80 ft. Since the recurrence interval was based on the period April-June only, which was considered the critical period for drainage needs, then 32 working days are gained during the period April-June by decreasing the spacing from 320 ft. to 80 ft.

There is no day by day record available of the water table heights calculated by Vaigneur and Johnson. It is, therefore, very difficult to determine the probability of having a high water table during any period within the months of April, May, and June. High water table usually occurs in April due to snowmelt and high antecedent moisture, and in May and June due to spring rains. This was supported by water-table measurements made by Vaigneur and Johnson during 1964-1965. Therefore, to simplify the problem, it will be assumed that, on the average, the number of days on which a high water table occurs during the one and one-half months from April 15 to June 1 is one-half that occurring during the three months April-June. Hence one-half of the working days gained during the critical period for drainage (April-June), by decreasing the tile spacing, will fall within the critical period for farm operations (April 15-June 1). Thus, 16 working days are gained during the critical period for farm operations by decreasing the tile spacing from 320 ft. to 80 ft. This is equivalent to

$(16)(7) = 112$ working hours (assuming 7 hours as a working day)

Equation 14 gives the cost of 1 hour delay of various farm operations. From Table 12, the timeliness factor, K', for planting corn and soybeans is 0.001. Therefore Equation 14 becomes

$$c = 0.001\ AYV$$

Assuming an average potential yield, Y, of 100 bushels/acre, and an average value, V, of one dollar/bushel, then the hourly cost is

$$c = (0.001)(100)(1)\ A$$
$$= 0.1\ A \text{ dollars/hour}$$

From Equation 15, the total cost of delay is equal to the hourly cost multiplied by the total delay in terms of working hours. Hence, a gain of 112 working hours would save the farmer

$$(112)(0.1)\ A = 11.2\ A \text{ dollars}$$

Therefore, decreasing the tile spacing from 320 ft. to 80 ft. will result in a gain of 11.2 dollars/acre. Since "no tile" comparison was not available, the 320-ft. spacing was considered indicative of no drainage.

It is important to mention again that tile drainage, in addition to providing a better root environment for plant growth, improves the trafficability of soil, and hence facilitates timely tillage operations. The gain estimated in this problem is the added economic benefit of tile drainage from increased soil trafficability and, therefore, timely farm operations.

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the effect of tile drainage on trafficability of soil and mobility of agricultural equipment. An estimate of the added economic benefit of tile drainage from increased mobility and timely crop planting was desired.

The above purpose was achieved by first relating the performance of vehicles to soil strength in terms of rating cone index. The rating cone index was evaluated by the cone penetrometer and remolding equipment. Relations were then developed between soil strength, moisture content, and depth to water table for poorly drained soils from field measurements and laboratory tests. Existing data were used in predicting the behavior of water table for various drain spacings and soil conductivities. A tile depth of 4 ft., a tile diameter of 0.5 ft., and a depth to the impervious layer below the drain of 4 ft., were assumed. The critical period for drainage needs was assumed to be the months of April, May, and June.

The results were applied to determine the increased number of days in which machine operations can be performed during the planting season when tile drains with various spacings are used. Central Iowa crops and field operation schedules were assumed. An estimate was then made of the added economic benefit of tile drainage from the standpoint of trafficability and timely crop planting.

On the basis of this study, the following conclusions were made:

1. When used in a knowledgeable way, the cone penetrometer is an extremely useful device. It has the advantage that many measurements can be made rapidly at the surface and at some depths below the surface.
2. The cone penetrometer is a satisfactory instrument for giving an indication of the in-place soil shearing strength.
3. There is a significant correlation between:
    a. Moisture content of soil in the critical layer (6- to 12-in. depth) and depth to water table
    b. Soil strength in terms of rating cone index and moisture content
    c. Soil strength in the critical layer and depth to water table
    d. Soil strength and degree of saturation
4. Relationships between soil strength in terms of rating cone index and moisture content obtained from

the laboratory tests agree with that obtained from the field.

5. An average increase of 16 working days is made during the critical period for farm operations by decreasing tile spacings from 320 ft. to 80 ft. in central Iowa.
6. The added economic benefit of tile drainage from improved soil trafficability for planting operations is about 11 dollars per acre for poorly drained soils in central Iowa.

There are two widely used methods for reducing untimely farm operations. The first method is by using a larger machinery system. This will reduce the time needed to perform various farm operations. The second method is by installing an adequate tile drainage system. This, in addition to providing better root environment for plant growth, will improve the trafficability of soil and, therefore, increase the time available for performing machine operations. The procedure of evaluating the effect of tile drainage on the timeliness of farm operations developed in this study will be useful in making economic comparisons between the two methods of reducing untimely farm operations. It may also be used in relating the effect of timeliness to the cost of alternative drainage systems.

Since most of the relations used in this study were developed for central Iowa, additional investigations should be pursued in adapting the procedure to other crops and other areas. Further studies should also extend such factors as tile depth, tile diameter, and depth to the impervious layer. Additional laboratory tests should include other soil-strength measuring devices and a wide range of soil types.

If air photos could be used in determining soil trafficability, a great amount of time and expense could be saved. A study should be made of the help air photos would give in determining soil trafficability.

In order to adapt the present investigation to actual field conditions, a study should be made in which tile systems are installed. Such a study may also be useful in evaluating the effect of stratification and variation in hydraulic conductivity which continually annoy the designer of tile systems.

BIBLIOGRAPHY

1. Bassett, J. R., McDaniel, A. R., and Knight, S. J. Variation in trafficability of four loess soils. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper No. 4-838. August 1966.

2. Bassett, J. R. and Meyer, M. P. Forecasting trafficability of soils; water table study at Crossett, Arkansas. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-331, Report 9. July 1968.

3. Beer, C. E. and Johnson, H. P. Fifteen-year summary of corn yields from tile drainage experiment in Edina soils of Iowa. A paper presented at the 1965 Winter Meeting of American Society of Agricultural Engineers, Chicago, Illinois. Agricultural Engineering Department, Iowa State University, Ames, Iowa. 1965.

4. Beer, C. E., Johnson, H. P., and Shrader, W. D. Yield response of corn in a Planosol soil to subsurface drainage with variable tile spacings. Iowa Agricultural and Home Economics Experiment Station Research Bulletin 540. September 1965.

5. Bekker, M. G. Introduction to terrain-vehicle systems. The University of Michigan Press, Ann Arbor, Michigan. 1969.

6. Bekker, M. G. Off-the-road locomotion. The University of Michigan Press, Ann Arbor, Michigan. 1960.

7. Bekker, M. G. Theory of land locomotion. The University of Michigan Press, Ann Arbor, Michigan. 1956.

8. Blake, G. R. Bulk density. In Black, C. A., ed. Methods of soil analysis. American Society of Agronomy Monograph 9, Part I: 374-390. 1965.

9. Blank, H. L., Davidson, D. T., Handy, R. L. and Roy, C. J. Military trafficability of soils in the Matanuska Valley, Alaska. Progress Report, June 1955-June 1956. Iowa Engineering Experiment Station, Iowa State University, Ames, Iowa. February 1957.

10. Buchele, W. F., Bockhop, C. W., and Marley, S. J. Influence of new practices upon farm equipment design. A paper presented at the 1968 National Combined Farm Construction and Industrial Machinery, Powerplant, and Transportation Meetings of the Society of Automotive Engineers, Milwaukee, Wisconsin. Agricultural Engineering Department, Iowa State University, Ames, Iowa. 1968.

11. DeBoer, D. W. and Ritter, W. F. Crop flood damage in depressional areas of north-central Iowa. A paper presented at the 1969 Mid-Central Region Meeting of American Society of Agricultural Engineers, St. Joseph Missouri. Agricultural Engineering Department, Iowa State University, Ames, Iowa. 1969.

12. Freitag, D. R. Penetration tests for soil measurements. American Society of Agricultural Engineers Transactions 11: 750-753. 1968.

13. Freitag, D. R. Wheels on soft soils, an analysis of existing data. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Report No. 3-670. 1965.

14. Frisby, J. C. and Bockhop, C. W. Influence of weather and economics on corn harvesting machinery systems. A paper presented at the 1966 Annual Meeting, Mid-Central Section, American Society of Agricultural Engineers, St. Joseph, Missouri. Agricultural Engineering Department, Iowa State University, Ames, Iowa. 1966.

15. Gill, W. R. and Vanden Berg, G. E. Soil dynamics in tillage and traction. United States Department of Agriculture, Agricultural Research Service Agriculture Handbook No. 316. 1967.

16. Kennedy, J. G., Collins, J. G., and Smith, M. H. Moisture-strength characteristics of selected soils in Thailand; analyses and application of data. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Report No. 3-791, Volume 1. August 1967.

17. Kennedy, J. G. and Hicks, T. E. Trafficability predictions in tropical soils; Puerto Rico study No. 2 (March 1962-November 1963). United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg,

Mississippi) Miscellaneous Paper No. 4-355, Report 6. November 1968.

18. Kennedy, J. G. and Rush, E. S. Trafficability of soils; development of revised mobility index formula for self-propelled wheeled vehicles in fine-grained soils. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-240, Eighteenth Supplement. March 1968.

19. Kilmer, V. J. and Alexander, L. T. Methods of making mechanical analysis of soils. Soil Science 68: 15-24. 1949.

20. Knight, S. J. and Freitag, D. R. Measurement of soil trafficability characteristics. American Society of Agricultural Engineers Transactions 5: 121-124, 132. 1962.

21. Knight, S. J. and Rula, A. A. Measurement and estimation of the trafficability of fine-grained soils. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper No. 4-441. August 1961.

22. Link, D. A. Farm machinery selection from systems economics. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University. 1958.

23. Marley, S. J. Machinery management and use on an Iowa Farm. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1960.

24. Marley, S. J. and Ayres, G. E. Influence of planting and harvesting dates on corn yield. A paper presented at the 1969 Winter Meeting of American Society of Agricultural Engineers, Chicago, Illinois. Agricultural Engineering Department, Iowa State University, Ames, Iowa. 1969.

25. Mathews, A. C., Handy, R. L. Davidson, D. T., and Roy, C. J. Trafficability studies of some Alaskan silts. Iowa Engineering Experiment Station Progress Report, June 1954-June 1955. July 1955.

26. McDaniel, A. R. Trafficability predictions in tropical soils; Colombia study (July 1962-July 1963). United

States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper No. 4-355, Report 4. November 1967.

27. McDaniel, A. R. Trafficability predictions in tropical soils; Costa Rica study No. 1 (January 1963-January 1965). United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper No. 4-355, Report 5. December 1967.

28. McDaniel, A. R. Trafficability predictions in tropical soils; Panama study No. 2 (October 1961-September 1963). United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper No. 4-355, Report 3. August 1966.

29. Meyerhof, G. G. The ultimate bearing capacity of wedge-shaped foundations. Fifth International Conference on Soil Mechanics and Foundation Engineering Proceedings 2: 105-109. 1961.

30. Ritter, W. F. and Beer, C. E. Yield reduction by controlled flooding of corn. American Society of Agricultural Engineers Transactions 12: 46, 47 and 50. 1969.

31. Rush, E. S. Soft-soil performance of a four-wheel-drive log skidder. American Society of Agricultural Engineers Transactions 12: 546-549, 551. 1969.

32. Rush, E. S. Trafficability tests with a two-wheel-drive industrial tractor. American Society of Agricultural Engineers Transactions 11: 778-782. 1968.

33. Rush, E. S. and Stinson, B. G. Trafficability tests with a two-wheel-drive industrial tractor. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper No. 4-917. August 1967.

34. Rush, E. S. and Temple, R. G. Trafficability tests in fine-grained soils with two vehicles with 9- to 10-ton wheel loads. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Miscellaneous Paper no. 4-879. March 1967.

35. Schwab, G. O., Kirkham, D., and Johnson, H. P. Effect of tile spacing on crop yield and water table level in a Planosol soil. Soil Science Society of America Proceedings 21: 448-452. 1957.

36. Tanner, C. B. and Jackson, M. L. Monographs of sedimentation times for soil particles under gravity or centrifugal acceleration. Soil Science Society of America Proceedings 12: 60-65. 1947.

37. Terzaghi, K. and Peck. R. B. Soil mechanics in engineering practice. 2nd ed. John Wiley and Sons, Inc., New York, New York. 1967.

38. United States Army Engineer School. Student reference; soils engineering. Section I, Volume II. United States Army Engineer School, Fort Belvoir, Virginia. February 1966.

39. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Forecasting trafficability of soils; development and testing of some average relations for predicting soil moisture. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-331, Report 5. June 1959.

40. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Forecasting trafficability of soils; information for predicting moisture in the surface foot of various soils. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi)) Technical Memorandum No. 3-331, Report 4. February 1957.

41. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Forecasting trafficability of soils; the development of methods for predicting soil moisture content. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-331, Report 3. October 1954.

42. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Strength-moisture-density relations of fine-grained soils in vehicle mobility research. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Report No. 3-639. January 1964.

43. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Summary of trafficability tests through 1963. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Contract Report 3-119. November 1964-June 1965.

44. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Trafficability of soils; a summary of trafficability studies through 1955. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-240, Fourteenth Supplement. December 1956.

45. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Trafficability of soils; analysis of existing data. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-240, Fifth Supplement. May 1949.

46. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Trafficability of soils; laboratory tests to determine effects of moisture content and density variations. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-240, First Supplement. March 1948.

47. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Trafficability of soils; tests on coarse-grained soils with self-propelled and towed vehicles, 1956 and 1957. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-240, Fifteenth Supplement. June 1959.

48. United States Army Engineer Waterways Experiment Station, Corps of Engineers. Trafficability of soils; tests on coarse-grained soils with self-propelled and towed vehicles, 1958-1961. United States Army Engineer Waterways Experiment Station, Corps of Engineers (Vicksburg, Mississippi) Technical Memorandum No. 3-240, Seventeenth Supplement. May 1963.

49. United States Department of the Army. Planning and design of road, airbases, and heliports in the theater of operations. United States Department of the Army Technical Manual TM5-330. September 1968.

50. Vaigneur, H. O. Water table frequencies of tile-drained land based on moisture balance. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1965.

51. Vaigneur, H. O. and Johnson, H. P. Drainage design based on moisture balance. American Society of Agricultural Engineers Transactions 9: 764-767. 1966.

52. van Schilfgaarde, J. Priorities for developing legal and economic research on water problems. In Massey, D. T., ed. Implementation of regional research in water-related problems. Pp. 1-12. Report of a seminar held at the Farm Foundation, Chicago, Illinois, Jan. 14, 1970. Madison, Wisconsin, Department of Law, University Extension, University of Wisconsin. 1970.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. Craig E. Beer for his guidance and counsel in selecting the problem and directing the study.

The author also wishes to thank Dr. Richard L. Handy, Dr. Howard P. Johnson, Dr. Robert E. Baumann, and Dr. Glenn Murphy, members of the committee, for their interest and suggestions.

The contributions of Dr. Dean R. Freitag of the Waterways Experiment Station, Vicksburg, Mississippi, and Dr. Wesley F. Buchele of Agricultural Engineering Department at Iowa State University are also especially recognized.

APPENDIX A: MOBILITY INDEX FORMULAS

a. Self-Propelled Tracked Vehicles:

$$\text{Mobility index} = \left[\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{track factor}} + \text{bogie factor} - \text{clearance factor} \right] \times \text{engine factor} \times \text{transmission factor}$$

wherein,

$$\text{contact pressure factor} = \frac{\text{gross weight in lb.}}{\text{area of tracks in contact with ground in sq. in.}}$$

weight factor: less than 50,000 lb. = 1.0
50,000 to 69,999 lb. = 1.2
70,000 to 99,999 lb. = 1.4
100,000 lb.or greater = 1.8

$$\text{track factor} = \frac{\text{track width in in.}}{100}$$

grouser[1] factor: grousers less than 1.5 in. high = 1.0
grousers more than 1.5 in. high = 1.1

$$\text{bogie}^{2}\ \text{factor} = \frac{\text{gross weight in lb. divided by 10}}{\text{(total number of bogies on tracks in contact with ground)} \times \text{(area of 1 track shoe in sq.in.)}}$$

$$\text{clearance factor} = \frac{\text{clearance in in.}}{10}$$

---

[1]A grouser is one of a set of cleats on a tractor wheel or track for increasing traction.

[2]A bogie is one of the weight carrying wheels on the inside perimeter of the tread of a tracked vehicle serving to keep the treads in line.

engine factor: 10 or greater hp per ton of vehicle wt = 1.0
less than 10 hp per ton of vehicle wt = 1.05

transmission factor: hydraulic = 1.0; mechanical = 1.05

b. Self-Propelled Wheeled Vehicles:

(1) All-wheel-drive vehicles.

$$\text{Mobility index} = \left[\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor} \times \text{grouser factor}} + \text{wheel load factor} - \text{clearance factor} \right] \times \text{engine factor} \times \text{transmission factor}$$

wherein,

$$\text{contact pressure factor} = \frac{\text{gross weight, lb.}}{\text{tire width, in.} \times \frac{\text{outside dia. of tire, in.}}{2} \times \text{No. of tires}}$$

Weight factor:

Weight range, lb (gross vehicle wt., lb. / No. of axles)	Weight factor equations
<2000	$Y = 0.553X$
2000 to 13,500	$Y = 0.033X + 1.050$
13,501 to 20,000	$Y = 0.142X - 0.420$
>20,000	$Y = 0.278X - 3.115$

$$X = \frac{\text{gross vehicle wt (kips)}}{\text{No. of axles}}$$

Y = weight factor

$$\text{tire factor} = \frac{10 + \text{tire width, in.}}{100}$$

grouser factor: with chains 1.05
without chains = 1.00

$$\text{wheel load factor} = \frac{\text{gross weight, kips}}{\text{No. of wheels (duals count as one)}}$$

$$\text{clearance factor} = \frac{\text{Clearance, in.}}{10}$$

engine factor: >10 hp/ton = 1.00
<10 hp/ton = 1.05

transmission factor: hydraulic = 1.00
mechanical = 1.05

(2) Rear-wheel drive only. If the vehicle is not equipped with an all-wheel drive, the cone index is computed according to the formula for all-wheel-drive vehicles, then multiplied by 1.4 to obtain the vehicle cone index.

c. Towed Tracked Vehicles:

$$\text{Mobility index} = \left[\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{track factor}} + \text{bogie factor} - \text{clearance} \right] + 30$$

wherein,

$$\text{contact pressure factor} = \frac{\text{gross weight in lb.}}{\text{area of tracks in contact with ground in sq. in.}}$$

weight factor: 15,000 lb. or greater = 1.0
below 15,000 lb. = 0.8

$$\text{track factor} = \frac{\text{track width in in.}}{100}$$

$$\text{bogie factor} = \frac{\text{gross weight in lb. divided by 10}}{\text{(total No. of bogies on track in contact with ground) X (area of 1 track shoe in sq. in.)}}$$

clearance factor = clearance in in.

d. Towed Wheeled Vehicles:

$$\text{Mobility index} = 0.64\left[\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor}} + \text{axle load} - \text{clearance}\right] + 10$$

wherein,

$$\text{contact pressure factor} = \frac{\text{normal tire pressure in lb. per sq. in.}}{2}$$

weight factor:

15,000 lb. per axle or greater	= 1.0
12,500 to 14,999 lb.	= 0.9
10,000 to 12,499 lb.	= 0.8
7,500 to 9,999 lb.	= 0.7
less than 7,500 lb.	= 0.6

tire factor: $\text{single tire} = \frac{\text{width in in.}}{100}$

$$\text{dual tire} = \frac{1.5 \times \text{width in in.}}{100}$$

$$\text{axle load} = \frac{\text{axle load in lb.}}{1000}$$

clearance = clearance in in.

APPENDIX B: CHARACTERISTICS AND VEHICLE CONE INDEX OF SOME AGRICULTURAL TRACTORS

Table 14. Vehicle characteristics, vehicle cone index for fifty passes, and vehicle cone index for one pass of some agricultural tractors

Name and model of tractor	Ford 3000, 8 speed, gasoline	John Deere 3020 syncro-mesh, diesel	Oliver 1855, diesel	Case 870, power shift, diesel	International Farmall 544, hydrostatic, gasoline
Gross weight, lb.	5,300	9,000	13,000	10,200	7,880
Front axle weight, lb.	1,700	2,100	2,900	2,700	2,050
Rear axle weight, lb.	3,600	6,900	10,100	7,500	5,830
Front tire width, in.	6.0	6.0	12.0	8.0	6.0
Rear tire width, in.	13.6	15.5	23.1	18.4	14.9
Front tire outside diameter, in.	29.1	29.1	38.1	31.9	29.1
Rear tire outside diameter, in.	51.5	61.7	71.2	65.2	61.6
Number of tires	4	4	4	4	4

Table 14. (Continued)

Name and model of tractor	Ford 3000, 8 speed, gasoline	John Deere 3020 syncro-mesh, diesel	Oliver 1855, diesel	Case 870, power shift, diesel	International Farmall 544, hydrostatic, gasoline
Number of axles	2	2	2	2	2
Ground clearance, in.	11	11	11	11	11
Drive	rear wheel	rear sheel	rear wheel	rear wheel	rear wheel
Chains	without	without	without	without	without
Transmission	mechanical	mechanical	mechanical	mechanical	hydrostatic
Engine horsepower, hp/ton	>10	>10	>10	>10	>10
Vehicle cone index for fifty passes	60	71	57	64	66
Vehicle cone index for one pass	45	53	43	48	50